

FILE COPY
NO. 5

CASE FILE
COPY

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 466

AIRCRAFT POWER-PLANT INSTRUMENTS

By HARCOURT SONTAG and W. G. BROMBACHER



REPRINT OF REPORT No. 466, ORIGINALLY PUBLISHED DECEMBER 1933

THIS DOCUMENT ON LOAN FROM THE FILES OF

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
LANGLEY AERONAUTICAL LABORATORY
LANGLEY FIELD, HAMPTON, VIRGINIA

RETURN TO THE ABOVE ADDRESS.

REQUESTS FOR PUBLICATIONS SHOULD BE ADDRESSED
AS FOLLOWS:

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
1724 F STREET, N.W.,
WASHINGTON 25, D.C.

1941

AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbrevia- tion	Unit	Abbrevia- tion
Length.....	l	meter.....	m	foot (or mile).....	ft (or mi)
Time.....	t	second.....	s	second (or hour).....	sec (or hr)
Force.....	F	weight of 1 kilogram.....	kg	weight of 1 pound.....	lb
Power.....	P	horsepower (metric).....		horsepower.....	hp
Speed.....	V	kilometers per hour.....	kph	miles per hour.....	mph
		meters per second.....	mps	feet per second.....	fps

2. GENERAL SYMBOLS

W	Weight= mg	ν	Kinematic viscosity
g	Standard acceleration of gravity= 9.80665 m/s^2 or 32.1740 ft/sec^2	ρ	Density (mass per unit volume)
m	Mass= $\frac{W}{g}$		Standard density of dry air, $0.12497 \text{ kg-m}^{-3}\text{-s}^2$ at 15° C and 760 mm ; or $0.002378 \text{ lb-ft}^{-3}\text{-sec}^2$
I	Moment of inertia= mk^2 . (Indicate axis of radius of gyration k by proper subscript.)		Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft
μ	Coefficient of viscosity		

3. AERODYNAMIC SYMBOLS

S	Area	i_w	Angle of setting of wings (relative to thrust line)
S_w	Area of wing	i_t	Angle of stabilizer setting (relative to thrust line)
G	Gap	Q	Resultant moment
b	Span	Ω	Resultant angular velocity
c	Chord	R	Reynolds number, $\rho \frac{Vl}{\mu}$ where l is a linear dimen- sion (e.g., for an airfoil of 1.0 ft chord, 100 mph , standard pressure at 15° C , the corresponding Reynolds number is $935,400$; or for an airfoil of 1.0 m chord, 100 mps , the corresponding Reynolds number is $6,865,000$)
A	Aspect ratio, $\frac{b^2}{S}$	α	Angle of attack
V	True air speed	ϵ	Angle of downwash
q	Dynamic pressure, $\frac{1}{2}\rho V^2$	α_0	Angle of attack, infinite aspect ratio
L	Lift, absolute coefficient $C_L = \frac{L}{qS}$	α_i	Angle of attack, induced
D	Drag, absolute coefficient $C_D = \frac{D}{qS}$	α_a	Angle of attack, absolute (measured from zero- lift position)
D_0	Profile drag, absolute coefficient $C_{D_0} = \frac{D_0}{qS}$	γ	Flight-path angle
D_i	Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$		
D_p	Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$		
C	Cross-wind force, absolute coefficient $C_c = \frac{C}{qS}$		

REPORT No. 466

AIRCRAFT POWER-PLANT INSTRUMENTS

By HARCOURT SONTAG and W. G. BROMBACHER
Bureau of Standards

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

HEADQUARTERS, NAVY BUILDING, WASHINGTON, D. C.

Created by act of Congress approved March 3, 1915, for the supervision and direction of the scientific study of the problems of flight (U. S. Code, Title 50, Sec. 151). Its membership was increased to 15 by act approved March 2, 1929. The members are appointed by the President, and serve as such without compensation.

VANNEVAR BUSH, Sc. D., *Chairman*,
Washington, D. C.

GEORGE J. MEAD, Sc. D., *Vice Chairman*,
Washington, D. C.

CHARLES G. ABBOT, Sc. D.,
Secretary, Smithsonian Institution.

HENRY H. ARNOLD, Major General, United States Army,
Deputy Chief of Staff, Chief of the Air Corps, War
Department.

GEORGE H. BRETT, Major General, United States Army,
Acting Chief of the Air Corps, War Department.

LYMAN J. BRIGGS, Ph. D.,
Director, National Bureau of Standards.

DONALD H. CONNOLLY, B. S.,
Administrator of Civil Aeronautics.

ROBERT E. DOHERTY, M. S.,
Pittsburgh, Pa.

ROBERT H. HINCKLEY, A. B.,
Assistant Secretary of Commerce.

JEROME C. HUNSAKER, Sc. D.,
Cambridge, Mass.

SYDNEY M. KRAUS, Captain, United States Navy,
Bureau of Aeronautics, Navy Department.

FRANCIS W. REICHELDERFER, Sc. D.,
Chief, United States Weather Bureau.

JOHN H. TOWERS, Rear Admiral, United States Navy,
Chief, Bureau of Aeronautics, Navy Department.

EDWARD WARNER, Sc. D.,
Washington, D. C.

ORVILLE WRIGHT, Sc. D.,
Dayton, Ohio.

GEORGE W. LEWIS, *Director of Aeronautical Research*

S. PAUL JOHNSTON, *Coordinator of Research*

JOHN F. VICTORY, *Secretary*

HENRY J. E. REID, *Engineer-in-Charge, Langley Memorial Aeronautical Laboratory, Langley Field, Va.*

SMITH J. DEFRAÑCE, *Engineer-in-Charge, Ames Aeronautical Laboratory, Moffett Field, Calif.*

TECHNICAL COMMITTEES

AERODYNAMICS
POWER PLANTS FOR AIRCRAFT
AIRCRAFT MATERIALS

AIRCRAFT STRUCTURES
AIRCRAFT ACCIDENTS
INVENTIONS AND DESIGNS

Coordination of Research Needs of Military and Civil Aviation

Preparation of Research Programs

Allocation of Problems

Prevention of Duplication

Consideration of Inventions

LANGLEY MEMORIAL AERONAUTICAL LABORATORY

AMES AERONAUTICAL LABORATORY

LANGLEY FIELD, VA.

MOFFETT FIELD, CALIF.

Conduct, under unified control, for all agencies, of scientific research on the fundamental problems of flight.

OFFICE OF AERONAUTICAL INTELLIGENCE

WASHINGTON, D. C.

Collection, classification, compilation, and dissemination of
scientific and technical information on aeronautics

TABLE OF CONTENTS

Introduction.....	Page 5
Tachometers.....	7
Engine log instruments.....	33
Engine thermometers.....	35
Pressure gages.....	40
Fuel quantity gages.....	44
Fuel flow indicators.....	48
Manifold pressure gages.....	53
References.....	56

REPORT No. 466

AIRCRAFT POWER-PLANT INSTRUMENTS

By HARCOURT SONTAG and W. G. BROMBACHER

SUMMARY

This report supersedes that on aircraft power-plant instruments, published in 1921 as N.A.C.A. Technical Report No. 129, which is now, on the whole, obsolete. Aircraft power-plant instruments include tachometers, engine thermometers, pressure gages, fuel-quantity gages, fuel flow meters and indicators, and manifold pressure gages. The report includes a description of the commonly used types and some others, the underlying principle utilized in the design, and some design data. The inherent errors of the instruments, the methods of making laboratory tests, descriptions of the test apparatus, and data in considerable detail on the performance of commonly used instruments are presented. Standard instruments and, in cases where it appears to be of interest, those used as secondary standards are described. A bibliography of important articles is included.

INTRODUCTION

PREFATORY NOTE

A general report on power-plant instruments was prepared at the Bureau of Standards in 1921 for the National Advisory Committee for Aeronautics (reference 5), which dealt mainly with instruments developed during the war. During the last 10 years aircraft instruments, including power-plant instruments, have undergone intensive development. This report covers the present status of power-plant instruments and was prepared at the Bureau of Standards with the approval and financial assistance of the National Advisory Committee for Aeronautics. A large amount of the material presented was obtained during the course of cooperative work with the Bureau of Aeronautics of the Navy Department.

TYPES AND FUNCTIONS OF POWER-PLANT INSTRUMENTS

Power-plant instruments are taken to include all types of instruments which are used on aircraft to indicate or record the performance of aircraft engines in flight. The instruments and the quantities measured are listed below:

Instruments	Quantity measured
Tachometers-----	Engine speed.
Recording tachometers-----	Do.
Running-time meters-----	Service time of engine.
Engine thermometers-----	Temperature of lubricant, cooling liquid, or cylinder.
Pressure gages-----	Pressure of lubricant or fuel.
Fuel quantity gages-----	Quantity of fuel available.
Fuel flow meters-----	Rate of fuel consumption.
Fuel consumed meters-----	Quantity of fuel consumed.
Combustion indicators-----	Degree of fuel combustion.
Supercharger pressure gages-----	Absolute pressure in intake manifold.

While power-plant instruments are of value to the pilot in connection with the normal operation of the engine, their function is also to assist him in detecting and locating the first sign of trouble. Their dependability thus becomes a matter of prime importance.

SCOPE OF THE REPORT

The discussion of each type of power-plant instrument includes a statement of the underlying principle used in making the measurement, a description of the instruments commonly used, the methods of making laboratory tests and data on the performance of typical instruments. In addition the standard instruments used in making the laboratory tests are described in most cases and, where it appears to be of interest, secondary standard instruments also. Instruments and methods not commonly used in aircraft but which are either of interest in this connection or have possible application in the future are briefly described.

RECENT GENERAL DEVELOPMENTS

Many developments during the past decade have affected aircraft instruments as a class. These have included the design of instruments having a linear vertical scale (now largely obsolescent), the standardization (and decrease) of the diameter of the dials of the commonly used instruments, a general improvement in over-all performance, and the adoption of a clockwise direction of rotation of the pointers for increasing values of the quantities measured. There has been a

number of other developments relating to power-plant instruments alone; and of these, two are mentioned as noteworthy—first, the improvement in the design and development of new types of distant-indicating electrical instruments and, second, the gradual development of various types of fuel flow meters.

A. VERTICAL SCALE INSTRUMENTS

Instruments having linear vertical scales were developed primarily in order to conserve the area of the instrument panel. Examples of power-plant instruments of this type are shown in figures 6 and 40. The design is particularly desirable in aircraft powered by more than one engine, since the several instruments can be mounted side by side, and synchronization is indicated when the pointers all lie in a horizontal line. Owing to the limited length of scale, the necessity for complicating the mechanism in order to obtain a motion of the pointer sufficiently linear, and the relatively high cost of manufacture, the vertical scale instrument is rapidly becoming obsolete.

B. STANDARDIZATION OF CASE SIZES

Largely through the initiative of the Bureau of Aeronautics of the Navy Department, experimental air-speed meters, altimeters, and tachometers were constructed by manufacturers in 1928, the diameter of the dials of which were reduced to $2\frac{3}{4}$ inches and the cases made uniform as regards mounting dimensions. Further, engine thermometers and fuel- and oil-pressure gages were made with uniform cases but with a smaller dial ($1\frac{1}{8}$ inches in diameter). These new dial and case dimensions were adopted as a standard by the Army and Navy Standards Conference of February 1929. Since then practically all service instruments have been standardized in one or the other of these two dial sizes with the corresponding mounting dimensions. In addition to the military air services, the Society of Automotive Engineers has also adopted the two new sizes as standard. The reduction in size is noteworthy. The dial of the tachometer previously considered standard was $3\frac{3}{4}$ inches in diameter and that of the pressure gage and thermometer 2 inches. The reduced size permits a reduction of the center to center distance between two tachometers mounted side by side from $4\frac{1}{2}$ to $3\frac{3}{4}$ inches. Examples of instruments with the new dial sizes are shown in figures 5 and 32.

C. UNIFORM DIRECTION OF POINTER ROTATION

Uniformity in the direction of rotation of the pointers (clockwise) with increasing values of the quantity measured, the advantages of which are obvious, is now an accepted requirement. As an example the pointer of the altimeter formerly rotated counterclockwise with increasing altitude while that of the tachometer rotated clockwise with increasing speed.

D. FITTINGS

The connections of the flexible shaft to the tachometer and to the engine have been standardized. Details are given later in the subsection on "Flexible drive shafts." The fittings on fuel quantity gages and manifold pressure gages for connecting to the lines of copper tubing have also been standardized both as to type and size. This fitting is described on page 26 of reference 20. A similar but different size fitting is used on fuel and oil pressure gages. Aluminum tubing and fittings are coming into use where practicable.

E. DISTANT INDICATING ELECTRICAL INSTRUMENTS

In multi-engined aircraft and in lighter-than-aircraft of the dirigible type, remote indicating instruments are required. This has led to improvement in the design and performance of electrical tachometers and the development of new types. As a result an electrical tachometer of the direct-current type with much improved performance and weighing less than 3 pounds, complete, is now available. Its indicator has a range of deflection of the pointer of nearly 300° of arc. (See fig. 12.) Tachometers of the alternating-current type have been developed by manufacturers. An electrical tachometer depending for its operation on the charge and discharge of a condenser has been developed, although it is not commercially available at the present time.

The thermocouple, the unbalanced Wheatstone bridge, and ohmmeters have been adapted for making measurements of temperature and other quantities on aircraft. Oil-pressure gages and thermometers utilizing an ohmmeter and thermometers of the thermocouple type are available. Types of electrical instruments which are independent of an outside source of electrical energy are preferred, other qualities being equal.

F. IMPROVEMENTS IN PERFORMANCE

The performance of most of the existing types of instruments has been slowly and steadily improved by minor modifications in design and more careful selection of the materials used in fabrication. This has been brought about in large part by the stimulus of changes made from time to time in military specifications. For example, a decided improvement followed the introduction of a definite vibration test, and poor performance at low temperatures was largely eliminated by requiring that tests be made at -35°C . instead of at -10°C . or -20°C . Further improvement in tachometers appears to be desirable with respect to the scale errors, the ability of the instruments to withstand vibration and to operate successfully under conditions of extreme low temperature. The trend has been toward more rigid inspection and tests on the part of both the instrument manufacturer and the buyer.

G. ILLUMINATION

The primary numerals and graduations, and the tips of the pointers of most service instruments are coated with luminous radium paint. This procedure has continued in spite of the development of methods of indirect electric illumination of the instrument board. The radium paint has the definite advantage of simplicity and the disadvantage of being more expensive.

Radium paint becomes brown with age and loses its luster which is stated to be caused by the use of poor oil in the adhesive. No short-time test for determining the quality of radium paint is known. Exposure of both good and poor radium paint to ultra-violet light and to temperatures up to 100° C. have failed to show any marked difference in behavior.

TACHOMETERS

USEFULNESS OF TACHOMETERS

A tachometer is an instrument which indicates speed of rotation and is used in aircraft to indicate continuously the speed of the engine crankshaft. The instrument is usually actuated by the camshaft, which on the conventional four-stroke cycle engine rotates at one half the speed of the crankshaft. The dial of the instrument is commonly graduated in revolutions per minute of the crankshaft.

It is desirable to know the rotational speed of the aircraft engine during, first, the course of normal operation; second, the flight testing of aircraft; and, third, the choice or adjustment of the propeller.

During the course of normal operation a knowledge of the speed is required before taking off in order (a) to determine that approximately the maximum power is available, and during flight (b) to detect engine trouble; (c) to maintain any desired speed in the case of a single engine or to synchronize approximately all engines at a given speed in multi-engine installations (in the latter case the final adjustment of the speed is normally made by listening to the beats in the sound produced by the propellers); (d) in emergencies, in combination with an air-speed meter, to indicate the deviations from level flight.

(a) Before taking off, the speed of the engine is observed while it is operating at full throttle. Under these conditions the maximum speed attained by the engine is somewhat lower than when the aircraft is in level flight at full throttle at a low altitude. Any drop from the usual value of this speed indicates improper functioning of the engine and the procedure is thus a simple test of the operating condition of the engine.

(b) Complete or even partial failure of a few engine parts results in a change in the operating speed, the indication of which should be of value to the pilot.

(c) It is generally assumed that all engines give service freer from trouble when operated somewhat below the normal maximum rated speed. This

reduced speed referred to as the "cruising speed" is determined by a number of factors such as smoothness of operation, rate of fuel consumption, etc. The tachometer indicates whether or not this desired speed is being maintained.

(d) Descent or climb of an aircraft is always accompanied by an increase or decrease, respectively, in the rotational speed of the engine together with an increase or decrease in the air speed, provided the engine controls remain in the same position. It follows therefore that a combined knowledge of the engine speed and the air speed may aid in indicating deviations from level flight.

In normal operation it is also desirable to synchronize the speed of engines on multi-engined airplanes. The tachometer is too insensitive to do this accurately. When the speeds are nearly the same, beats are distinctly heard which afford a measure of the difference in the speeds and a guide to synchronizing.

In the flight testing of aircraft it is necessary that certain conditions of operation remain constant, one of which is the rotational speed of the engine, while changes in other conditions of operation are measured.

A knowledge of the rotational speed of the engine is necessary when determining the suitability of the propeller or propeller setting. The use of a propeller whose pitch angle may be varied during flight requires a knowledge of the engine speed in order that the pitch setting may be adjusted properly.

CLASSIFICATION

It is obvious that the indication of the speed must be at a distance from the aircraft engine, and this involves the use of instruments commonly called distant-indicating. Tachometers are classified here on the basis of the particular means used to connect the indicator to the engine or the actuating element at the engine. Common methods of making this connection are by means of (a) a flexible shaft rotating at a speed proportional to that of the engine (b) an electrical current controlled by an element rotated by the engine and (c) an air pressure dependent on engine speed. Instruments with these respective methods of transmission will be called the mechanical, electrical, and pneumatic types.

The mechanical type includes the centrifugal, chronometric, magnetic drag, viscous drag, inertia and a number of other tachometers.

The electrical type includes the direct current, the alternating current, the solenoid-operated chronometric, and the commutator-condenser instruments.

The various pneumatic instruments are the same in principle and differ only in design details.

Other types of tachometers are essentially unsuited for use on aircraft. These instruments include the tachiscope, the various forms of stroboscopes, and the electrical type utilizing synchronous motors. The resonance or vibrating reed instrument has not been

used on aircraft up to the present but may be of possible use in the future.

MECHANICAL TACHOMETERS

Instruments of the mechanical type are used more extensively on aircraft than the others due to their

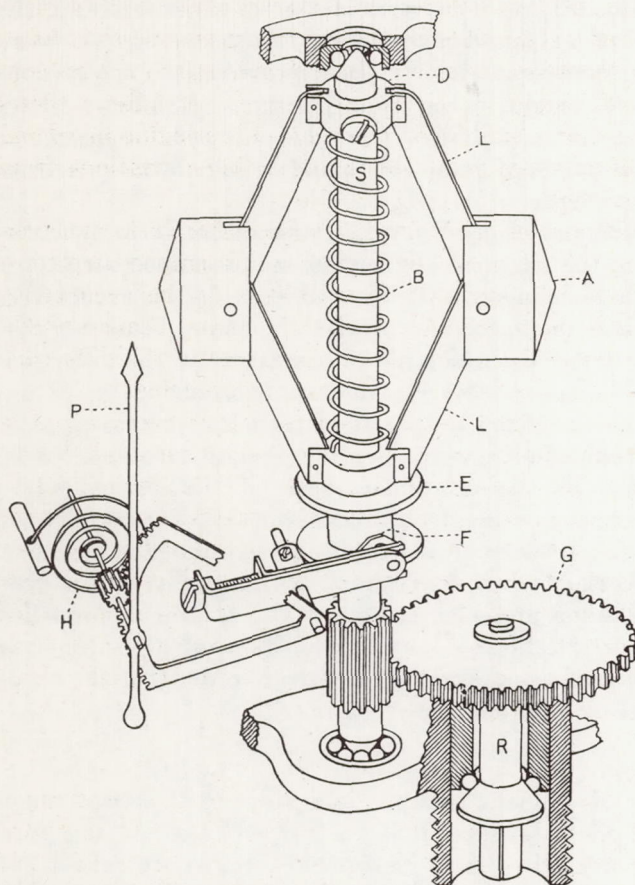


FIGURE 1.—Diagram of centrifugal tachometer.

relatively low cost and their reliability of operation. These tachometers are operated by means of a flexible drive shaft extending from the engine to the tachometer. The latter is usually installed on the instrument board.

The practical impossibility of obtaining smooth performance from the long drive shaft needed to connect most outboard engines to the tachometer on the instrument panel has led to the practice in such cases of attaching the tachometer to the engine mount in such a position that the dial may be readily observed from the cockpit. Obviously this arrangement is unsatisfactory and especially so when the weather is unfavorable for good visibility.

A. CENTRIFUGAL TACHOMETERS

Principle of operation.—In this instrument the centrifugal force produced by the rotation of weights is balanced by a spring. The deflection of this spring is a measure of the speed of rotation and is indicated by a pointer after magnification by means of a suitable mechanism. A diagram of a typical mechanism is

shown in figure 1. The centrifugal element is similar to that of the fly-ball governor, and usually consists of 2 or 3 brass weights A (fig. 1), each pinned to 2 links L. The upper links are attached to sleeve D which is clamped to shaft S, and the lower links to sleeve E, which is free to slide along the shaft. The two sleeves are held apart by the helical spring B. The flexible drive shaft is connected to shaft R and drives shaft S through gear G. As the speed of rotation of the weights is increased, they fly outward and draw sleeve E upward, thus compressing spring B until the centrifugal force is balanced by the force exerted by the spring. A pin or shoe F held in bearing on the sleeve E by the hairspring H is deflected upward as the spring is compressed. This deflection is amplified and transmitted to the pointer through the sector and pinion as shown in the figure.

Elementary theory.—An expression for the deflection of the sliding sleeve E is easily obtained for the simple form of mechanism shown in figure 2. Since it is obvious that the expression to be derived will be independent of the number of revolving masses and links, the sum of the masses and the sum of the tensions in the links only will be considered. It is assumed that each of the masses is pivoted at its center of gravity and that when the speed of rotation is zero the main-

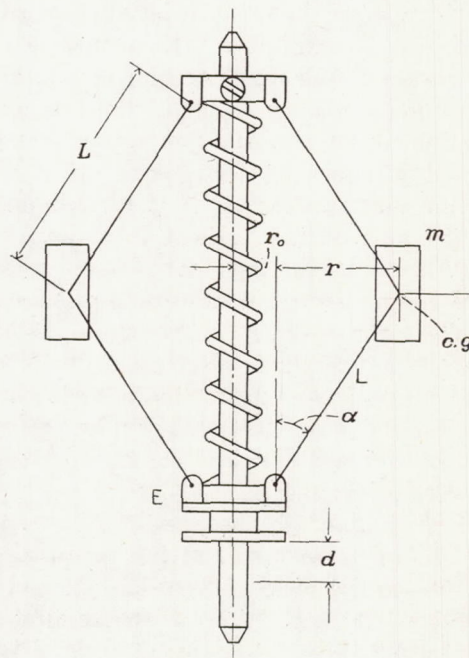


FIGURE 2.—Diagram of centrifugal element of tachometer.

spring is under a compressional stress and the effective radius of the masses is not zero. The sum of the tensions T in the lower links of the mechanism due to the centrifugal force acting on the sum of the revolving masses m is equal to

$$T = \frac{m(r + r_0)\omega^2}{2 \sin \alpha} \quad (1)$$

where r_o is the distance of the center of gravity of mass m from the axis of rotation when the speed is zero, $(r+r_o)$ is the distance when the angular velocity is ω , and α is the angle between the link L and the axis of rotation. This tension is balanced by that due to the compressive force F exerted by the spring and the gravitational weight of mass m . Therefore

$$T = \frac{F}{\cos \alpha} + \frac{mg}{2 \cos \alpha} \quad (2)$$

where g is the acceleration of gravity.

The compressive force $F = sd + sd'$ where d is the deflection of both the sliding sleeve and of the spring, d' the initial deflection of the spring, and s the stiffness of the spring. The stiffness is defined as the load required to produce unit deflection.

Substituting $sd + sd'$ for F in equation (2) and equating the identities of equations (1) and (2) there results

$$\frac{s(d+d')}{\cos \alpha} = \frac{m\omega^2}{2 \sin \alpha} (r+r_o) - \frac{mg}{2 \cos \alpha} \quad (3)$$

The first term on the right-hand side of equation (3) is usually large compared to the second term so that the latter is dropped.

From the geometry of the linkage the following relations are obtained:

$$r = \frac{\sqrt{4Ld-d'^2}}{2} \quad (4)$$

$$\sin \alpha = \frac{r}{L} = \frac{\sqrt{4Ld-d'^2}}{2L} \quad (5)$$

and

$$\cos \alpha = \frac{\sqrt{L^2-r^2}}{L} = \frac{2L-d}{2L} \quad (6)$$

L here represents the length of one of the links.

Substituting these values of $\sin \alpha$ and $\cos \alpha$ in equation (3) there is obtained:

$$\omega^2 = \frac{2s(d+d')}{(2L-d) \left(\frac{m}{2} + \frac{mr_o}{\sqrt{4Ld-d'^2}} \right)} \quad (7)$$

It is convenient to express the deflections d and d' as percentages of the length of the link L . Thus $d = KL$ and $d' = ML$. Also more convenient units are

obtained by using the relations $\omega = \frac{2\pi N}{60}$ and $m = \frac{w}{g}$

where N is the number of revolutions per minute and w is the weight of mass m . Substituting these values for d , d' , w , and m in equation (7) and taking the square root of both sides of the equation there results:

$$N = \frac{60}{2\pi} \sqrt{\frac{2s(K+M)}{\frac{w}{g}(2-K) \left(\frac{1}{2} + \frac{r_o}{L\sqrt{4K-K^2}} \right)}} \quad (8)$$

If r_o and L in the above equation are in inches and s is in pounds per inch, g must be expressed in inches per second per second.

The relation between K , the relative deflection of the sliding sleeve, and N , the speed of rotation of the weights, given by formula (8) was computed for the case when $M=0$, $w=0.054$ pound, $g=386.4$ inches per second per second, $s=10.8$ pounds per inch, and $r_o/L=0.625$ and is given in figure 3. These values were obtained by measurements made on a Jones tachometer. The graph shows that for values of K from 0.2 to 1.0 the relation between K and N is sufficiently linear for practical purposes and that the curve is concave upward for lower values of K and concave downward for large values. It can be further shown that when $M=0$, only r_o/L need be considered as a factor in affecting the extent of the linear portion of the curve. As the values of r_o/L are increased up to 1.0, the approximately linear portion of the curve is extended

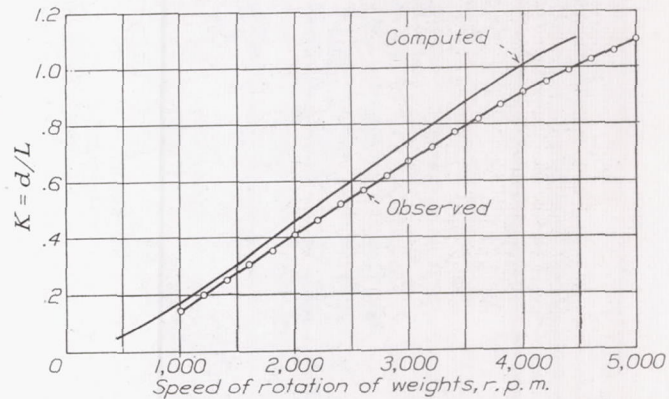


FIGURE 3.—Computed and experimental values of the ratio of the deflection d of the sliding collar to the length L of the link for various speeds of rotation of the weights of a Jones centrifugal tachometer.

but slightly beyond the limiting values of K given above but the rate of change of curvature is much less for the values of K beyond these limits.

The deflection of the sliding sleeve corresponding to the rate of rotation of the Jones tachometer was also measured and is given in figure 3 by the curve marked "observed." The agreement is not good with respect to coincidence which is probably due to the fact that the initial tension M in the spring was not zero, as assumed in the computation, and that r_o was taken as the distance from the axis of rotation to the pin instead of to the center of gravity of the weight. No attempt was made to eliminate the discrepancy by additional measurements since the formula is sufficiently established for use in obtaining first-order accuracy.

Description of centrifugal instruments.—A number of centrifugal tachometers are made in this country. The Stewart-Warner tachometer is shown in figure 4, the Pioneer in figure 5, and a Pioneer experimental vertical scale instrument in figure 6. In the latter instrument the two links holding the weights also act as the main spring.

The principal difference between the various makes of aircraft centrifugal tachometers lies in the method of transferring the deflection of the sliding sleeve to the multiplying mechanism. This is the point at which practically all of the wear affecting the calibration of the instrument occurs. In the Pioneer tachometer (fig. 6) the contact point is on the axis of the main shaft which has been bored to permit the insertion of a plunger the outer end of which is connected with the multiplying mechanism. In the Friez tachometer a

attached to the pointer shaft. In order to reduce the pressure of contact between the pin and the rotating flange to the allowable minimum it is the practice to employ a hair spring as light and as flexible as possible.

The maximum deflection of the main spring of a centrifugal tachometer is usually large. Thus for the instrument for which data are given in figure 3 the deflection at the highest speed is over one half of the original length of the helical spring. Due to limitations of space it is practically impossible to de-

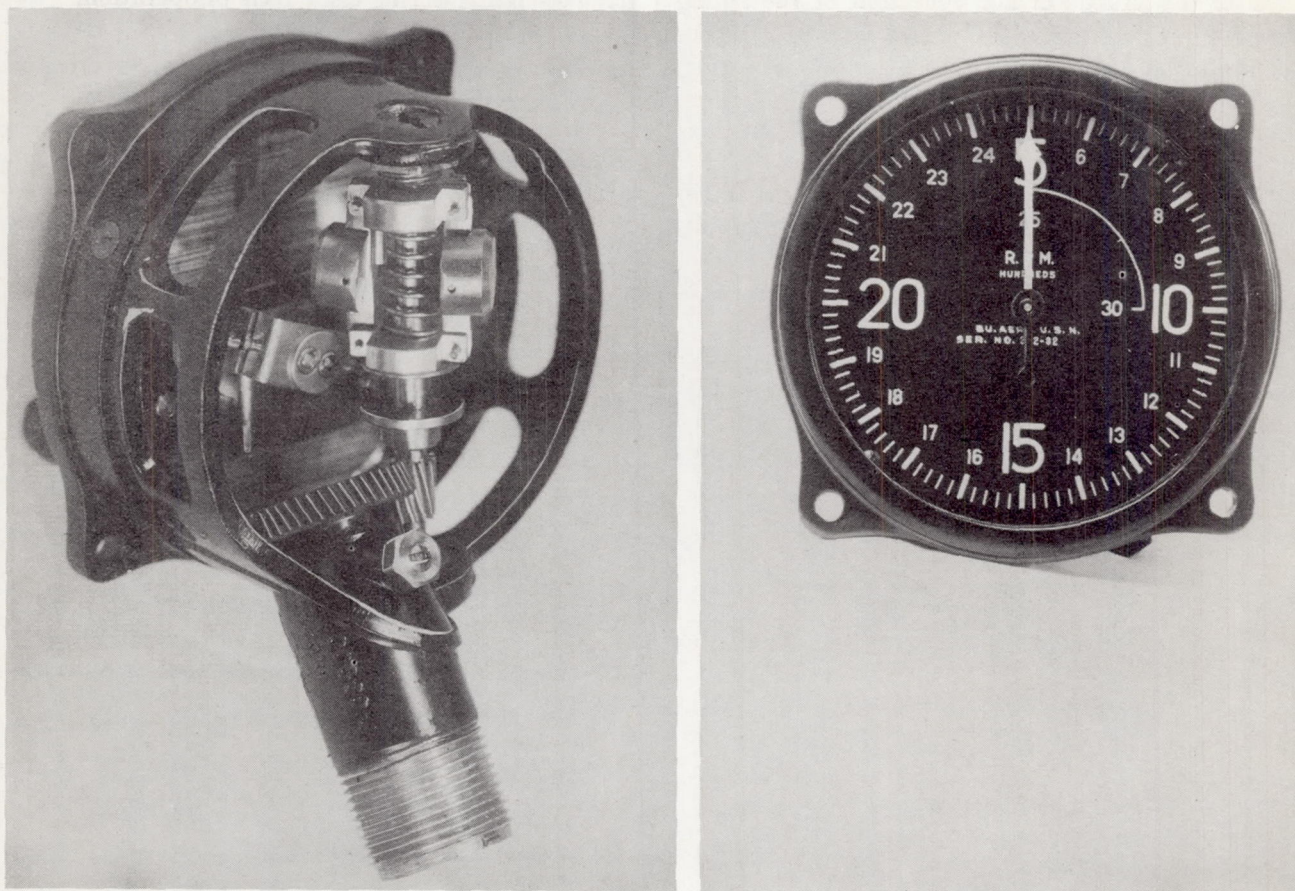


FIGURE 4.—Mechanism and dial of the Stewart-Warner centrifugal tachometer.

sapphire pin attached to the primary lever of the multiplying mechanism bears against a flange on the sliding sleeve. In the Stewart-Warner tachometer, shown in figure 4, a shoe made of wear-resisting alloy is pivoted to the primary lever of the multiplying mechanism and bears against a hardened steel flange which has been forced onto the sliding sleeve.

When a sapphire is used to transmit the deflection of the sliding sleeve, it should be provided with metallic reinforcement. Experience has shown that the accelerative force accompanying a sudden opening of the throttle is in some instances great enough to fracture the jewel.

In all of the mechanisms described the force exerted on the sliding sleeve by the multiplying mechanism at the contact point is that imposed by the hair spring

sign a spring suitable for the purpose that is not highly stressed at the higher speeds of the range of the instrument without at the same time requiring an excessive magnification of the deflection of the sliding sleeve. It is essential therefore that the main spring be made of a material having a high elastic limit.

It is the practice in this country to operate the governor elements of aircraft centrifugal tachometers at a speed four times that of the drive shaft (twice the speed of the engine crankshaft) which is accomplished by means of suitable gearing. (See fig. 1.) This greater speed permits the use of smaller rotating masses and a reduction of the dimensions of the instrument. The error introduced by tipping the instrument is greatly minimized by operating the governor elements at the higher speeds. An exception to this practice,

however, is found in one model of the Reliance tachometer in which the gearing is eliminated and the governor element is rotated at the speed of the cam-shaft.

The standard range of tachometers used in the military air services is now 500 to 3,000 r.p.m. corresponding to a pointer motion of $1\frac{1}{4}$ revolutions (fig. 4). The graduations are usually evenly divided. The graduations below 500 r.p.m. are not needed and are omitted since it is not practical to obtain accurate indications owing to the much smaller deflection of the spring

peratures largely due to congealing of the lubricant, but this disadvantage would be obviated by the development of a more suitable lubricant.

CHRONOMETRIC TACHOMETER

Principle of operation.—The chronometric tachometer is essentially a revolution-counting device, the operation of which is automatically governed by an escapement mechanism so as to periodically integrate and indicate the number of revolutions of the drive shaft occurring during each cycle of operation.

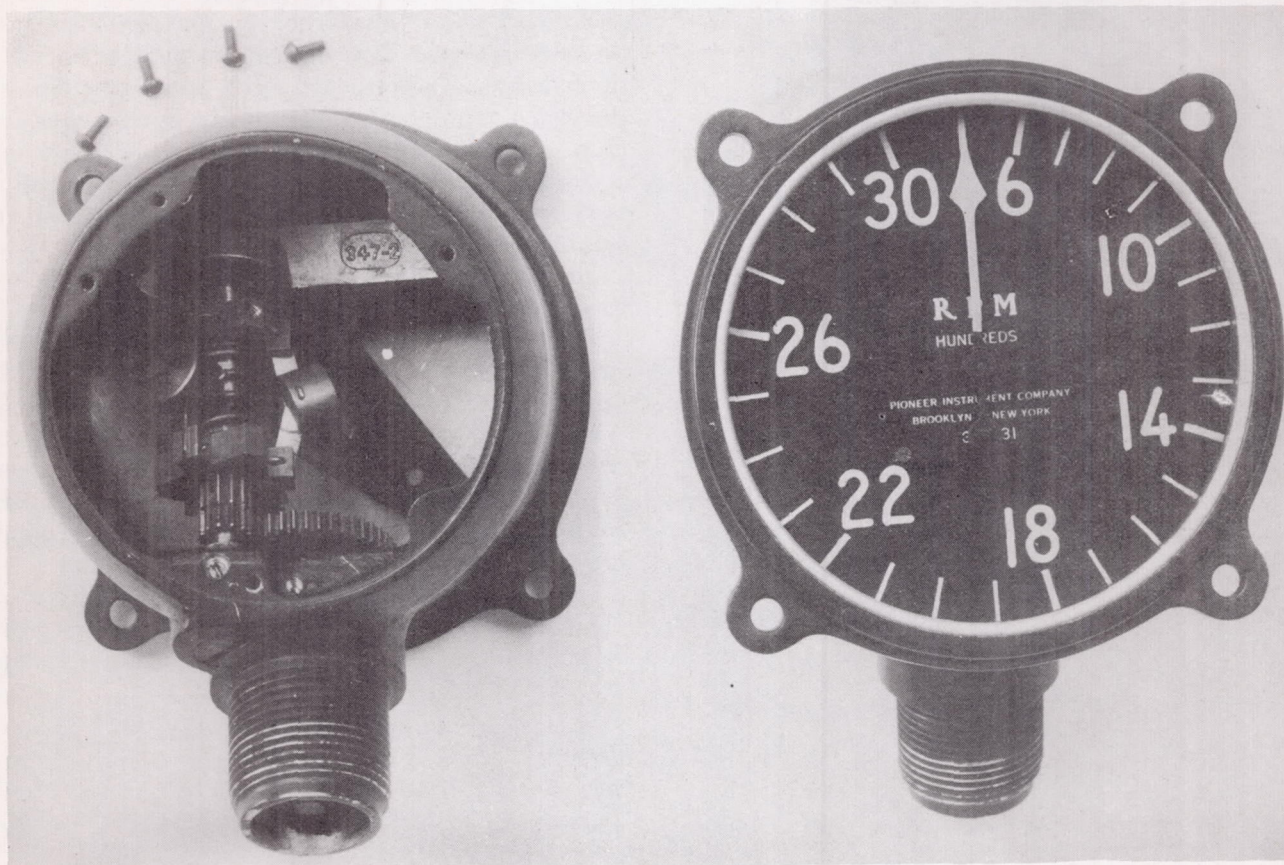


FIGURE 5.—Dial and mechanism of the Pioneer centrifugal tachometer.

per unit change in velocity. Thus in figure 3 the change in deflection measured when the speed of the weights (two times engine speed) is changed from 0 to 1,000 is only about one half of that when the speed is changed from 1,000 to 2,000 r.p.m.

Characteristics of centrifugal tachometers.—The centrifugal tachometer is simple in design and inherently rugged. It indicates the instantaneous speed with but negligible time lag and independently of the direction of rotation of the drive shaft. Its mechanism is easily adjusted to correct small errors in indication, which is an advantage in manufacture and maintenance. On the other hand, the centrifugal tachometer is difficult to lubricate after installation and of course requires the use of a flexible drive shaft. The frictional drag of the latter increases greatly at low tem-

The essential parts of the mechanism of the ordinary chronometric tachometer are (a) driving mechanism, (b) escapement mechanism, (c) power supply for the escapement mechanism, and (d) counting mechanism.

Van Sicklen.—Referring to figure 7, which is a diagram of the Elgin-Van Sicklen tachometer, the driving mechanism is identified by the letters A and B and includes a mechanism to rectify the motion of the drive shaft, whether clockwise or counterclockwise, into a unidirectional motion of rotation. The escapement mechanism, shown in the figure at C, governs the speed of rotation of the cams, one of which is shown at J. The power supply for the escapement mechanism is contained in drum M and consists of a spiral spring, the inner coil of which is fastened to the shaft connected with the driving mechanism, while the outer

coil normally bears with some friction against the inner cylindrical surface of the drum. This mechanism

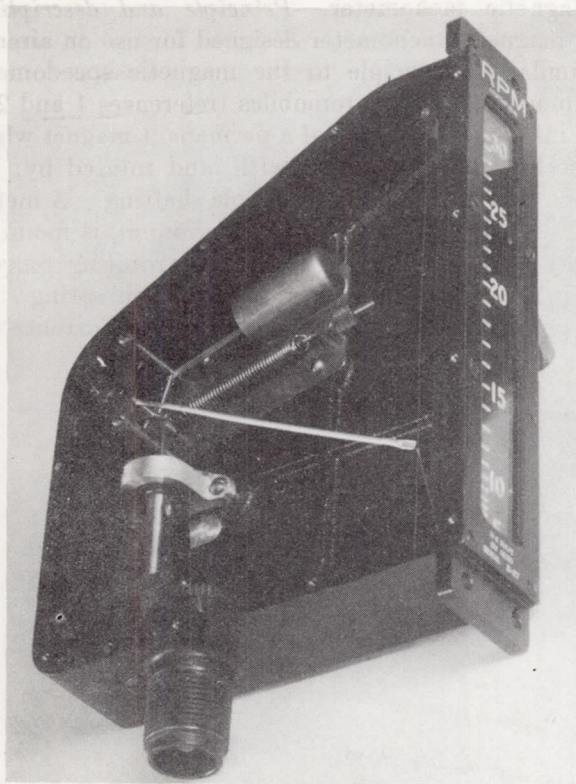


FIGURE 6.—Pioneer centrifugal tachometer with linear scale.

transmits a torque sufficient for rotating the cams, slippage occurring when the torque becomes excessive. The counting mechanism is identified in the figure by

counting gear **D** is first placed in mesh for a period of one second with gear **F** which is actuated by the drive shaft. The engagement of the two gears **D** and **F** is produced through the intermediate gear **E** actuated by a cam, one lobe of which is shown at **J**. By means of a pin and floating link mechanism shown at **G**, gear **H** and the pointer which is rigidly fastened to the same shaft as gear **H**, are caused to rotate through an angle proportional to the total number of revolutions over a period of one second. Gear **H** is essentially a ratchet gear and is provided with a pawl which is also actuated by a cam (not shown in the figure). At the end of the one second period the pointer remains stationary while the counting gear **D** is disengaged and, by means of the hair spring **K**, returned to its initial position. At the end of the following second the cycle is repeated. If the speed of the drive shaft has increased, the pointer is caused to increase its reading to correspond with the new average speed. If the speed has decreased, the pointer is released by the aforementioned pawl and under the influence of hairspring **L** returned to a position corresponding to the decreased speed.

The complete cycle of operation requires 2 seconds of time. When the speed varies greatly, the resulting periodic fluctuation of the pointer is disconcerting. When the speed varies only slightly, the pointer will change its position at the end of every 2-second interval by steps of 10 r.p.m. due to the fact that the number of teeth on gear **H** is 250 while one revolution of the pointer corresponds to a speed range of 0 to 2,500 r.p.m.

Shortly after the introduction of this instrument by the manufacturer its mechanism was greatly improved by substituting the double-roller type for the single-

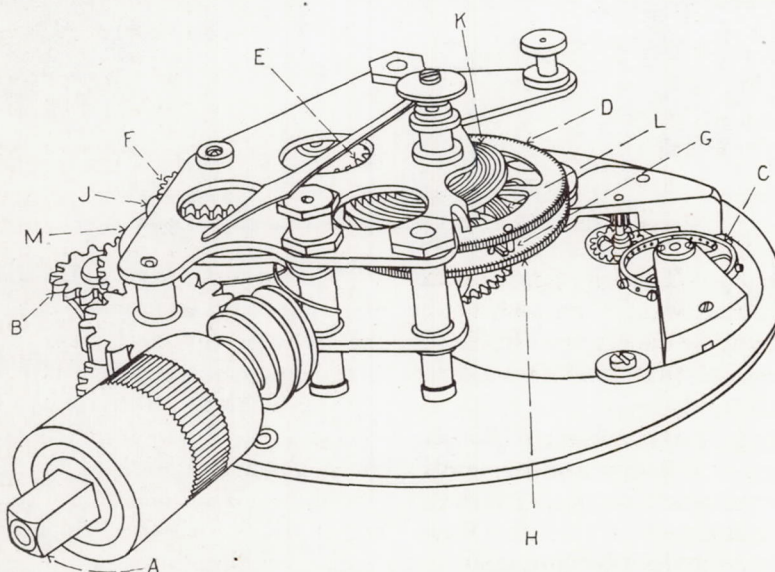


FIGURE 7.—Diaphragm of Van Sicklen (Elgin) chronometric tachometer.

gears **D** and **H**. Its function is to produce a deflection of the pointer corresponding to the speed of the driving mechanism.

The operation of the instrument (reference 29) may be understood by again referring to figure 7. A

roller type of escapement. See figure 8 and reference 23. This has resulted in more certain starting and longer life. The balance wheel of this escapement is of the bimetallic form commonly used to secure temperature compensation.

Hasler and Jaeger tachometers.—Two additional makes of chronometric tachometers, the Hasler "Tel" (reference 25) and the Jaeger, both of which are imported, are being used to some extent. All of the chronometric tachometers are fundamentally similar with regard to the principle of operation. The chief differences between them lie for the most part in the details of design and arrangement of their component parts. The following table gives a few of the principal characteristics of recent models of each of three makes of tachometers.

Make	Weight	Usual range	Period of cycle	Pointer deflection
	Ounces	R. p. m.	Seconds	Degrees
Van Sicklen.....	13	0-3500	2	504
Hasler Tel.....	21	0-2500	1	360
Jaeger.....	20	0-3500	1	504

Comparison of centrifugal and chronometric tachometers.—The chronometric tachometer has many of the characteristics which are desirable in an instrument designed for use on aircraft. In comparison with the centrifugal tachometer three favorable characteristics are outstanding: (a) Low speeds in the range 0 to 500 r.p.m. are indicated; (b) the indications have an equal or greater initial accuracy and maintain this accuracy throughout the life of the instrument; and (c) the indications are free from lag due to friction in the mechanism. In addition to these comparative advantages the chronometric instrument has (d) a scale uniformly divided in units of r.p.m. and is (e) easy to adjust for minor deviations from the proper calibration which is done by adjusting the period of the balance wheel.

The instrument suffers by comparison with the centrifugal tachometer in that (a) the indication follows changes in speed at intervals of 1 or 2 seconds, depending upon the design, which experience shows is troublesome in estimating the average speed during minor fluctuations, and (b) the average speed of the previous interval of time is indicated, not as is more desirable, that at the instant of observation. The centrifugal tachometer indicates the instantaneous speed with a lag caused by the inertia of the mechanism, which has, however, the practical advantage of smoothing out the minor rapid fluctuations in speed, thus aiding the observer in determining the average speed. A further point against the chronometric instrument which is perhaps secondary is (c) that the mechanism is inherently complicated and, in a number of designs, not sufficiently rugged for aircraft use.

C. OTHER MECHANICAL TACHOMETERS

Other ingenious mechanisms have been designed for measuring speed of rotation by direct coupling to the rotating body. Most of these have no advantage over the centrifugal or chronometric tachometer for aircraft

use. A few of these mechanisms will be briefly described.

Magnetic tachometer.—*Principle and description:* The magnetic tachometer designed for use on aircraft is similar in principle to the magnetic speedometer commonly used on automobiles (references 1 and 21). The instrument consists of a permanent magnet which is mechanically connected with, and rotated by, the engine through a length of flexible shafting. A metallic disk or cylinder, usually of aluminum, is mounted axially in close proximity with the rotating magnet and is restrained from revolving by a hair spring. As the permanent magnet is rotated, eddy currents are

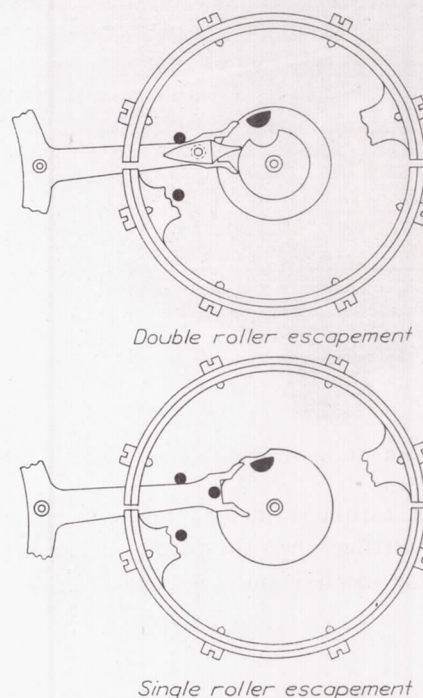


FIGURE 8.—Diagram of double and single roller escapements.

induced in the disk, the magnetic field of which interacts with the field of the permanent magnet so that the disk is subject to a couple tending to rotate it with the magnet. In short the principle of operation is that of Arago's disk, which is described in most text books of physics. Since the induced torque is a function of the speed of rotation of the magnet, the angular deflection of the disk is a measure of the speed. For use in aircraft a pointer is attached to the disk, and a dial graduated in r.p.m. is provided.

An attempt was made to adapt the instrument to aircraft use in 1918. The Warner instrument is described in reference 1, and 3 German types in reference 7. A later development is the A C instrument (reference 38), which has not come into any extended use. The weight of the latter instrument is 20 ounces.

Characteristics.—The magnetic drag tachometer is simple in design and construction and has a smooth pointer motion. Mechanical wear of the parts affects

the clearance between the disk and rotating magnet, giving rise to relatively large changes in calibration. In the latter respect the performance of the instrument appears to be more dependent on wear than that of the centrifugal tachometer. It is also necessary to shield the instrument magnetically in order to avoid interfering with the indications of the magnetic compass. The indicating disk has a free period of vibration, quite large in comparison with that of commonly used tachometers, which gives rise to a relatively large time lag in indicating a varying speed.

Inherently the instrument indications are excessively affected by temperature, but methods of compensation have been developed which are sufficiently effective for automobile speedometers and perhaps promising for aircraft tachometers.

The earlier methods of temperature compensation depended upon changing the air gap in the magnetic

for friction sufficient to hold a given position, and has attached to it a rigid strip (not shown in the figure) which overhangs the brass disk C, almost touching the gear A.

At the start of a cycle of operation, the pin on arm B engages lever E and disk C moves with the rotating gear A, winding up hair spring D. The motion in common of A and C is interrupted once every revolution of A by a pin fixed to the case which disengages E from B. The tension in the hair spring D causes disk C to reverse its motion and rotate to the position where E and B again come into contact. At the time E and B are disengaged a pawl on arm B catches on the strip attached to the pointer shaft so that the pointer shaft moves with gear A. At the point where the lever E, carried by the returning disk C, and the pin on B of the advancing gear A meet, the pointer is released by a cam action of arm E and holds this posi-

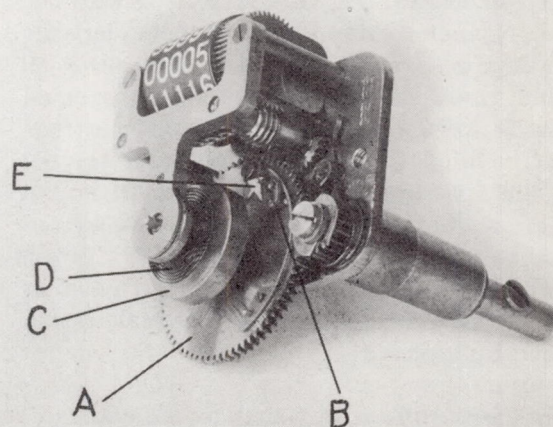
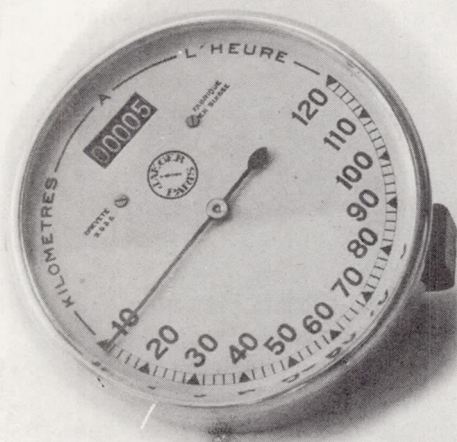


FIGURE 9.—Inertia tachometer.

circuit with temperature by means of a bimetallic strip (Warner, reference 5) or by a liquid-filled capsule (Ihle, reference 7). Later methods depend upon the use of a magnetic shunt of copper-nickel-iron alloy in the manner described in the section on "Electric Tachometers." Difficulties arise in this method, due to the fact that the effect of temperature on the uncompensated instrument is not the same function of temperature as that of the effect on the compensator.

Inertia tachometer.—The inertia tachometer of Swiss manufacture (Jaeger) in use abroad for many years as an automobile speedometer is very simple and interesting. A comparatively heavy brass gear A (figure 9) carrying an arm B very close to its periphery is rotated by a pinion at a speed proportional to the engine speed. A heavy disk C is mounted concentrically with the gear but on an independent shaft. A hair spring D is attached to the shaft of C and to a member fixed with respect to the case. Lever E is integral with disk C. The pointer shaft is free, except

tion until the above cycle is again repeated. The deflection of the pointer is thus nearly proportional to the speed of rotation. If a subsequent speed is lower, the pointer is moved backwards by E on disk C engaging the strip on the pointer.

The average speed for the previous interval of time is indicated as in a chronometric tachometer, with the difference that the time interval is variable, being short for high speeds and long for low speeds. The condition for obtaining an evenly divided scale is that the inertia disk C should have a constant velocity. This is achieved in large measure by making the scale short — 180° of arc in figure 9. This inherently short length of scale is a serious disadvantage to its use in aircraft. Variation in the temperature of the instrument will affect the stiffness of the hairspring and may vary the friction in the pivots of the inertia disk.

Other types.—The viscous drag tachometer using either air, mercury or other fluid for operation has entirely disappeared from use in aircraft. Instru-

ments of this type which have been constructed for aircraft use include the American Waltham (reference 5), the French Atmo (reference 5), and a German instrument by Lehmbek (reference 7). The first mentioned instrument used air and the other two used mercury as the fluid.

A differential drive tachometer of unique design has been proposed by A.E.G. (German), but has apparently not been used on aircraft (reference 7).

Liquid centrifugal tachometer.—The liquid Veeder instrument described in the section on "Testing Equipment" in a design with a much shortened scale was used to a slight extent in the early days of airplanes. The measurement of pressure, as is here necessary, by means of a liquid column involves, compared to instruments of other types, (a) an excessive position error, (b) lack of sensitivity in a small bulk, and (c) difficulty in retaining the liquid.

The mechanism of the friction disk tachometer designed by Behrens (French) (references 17 and 7) consists of two disks, one driven at constant speed and the other at a speed proportional to that of the engine. The axes of rotation are at right angles and the edge of the variable speed disk is in frictional contact with the constant speed disk. The variable speed disk moves along its shaft, which is essentially a worm gear, until the peripheral speeds of the points of contact are equal. The position of the disk, and thus the speed, is indicated by a pointer connected to the disk by a pinion and rack. The constant speed disk is also driven by the engine, a frictional clutch controlled by a centrifugal governor in a cylindrical barrel serving to obtain constant speed. The instrument indicates rotation in either direction, two pinions driven differentially being used with an automatic clutch so as to drive the disks in a uniform direction.

In a later design, known as the Delta tachometer and described by Aera (1926), a cone is used instead of the constant speed disk.

The performance of the instrument is not as satisfactory as other types (reference 17), which, as might be expected, is due to the difficulty of maintaining the necessary constancy of friction under the conditions of use.

D. FLEXIBLE DRIVE SHAFTS

The flexible drive shaft used with the tachometer consists of a torsionally stiff but otherwise flexible driving element and a casing capable of guiding and protecting it and retaining without leakage a suitable lubricant. The flexible driving element is composed of a single strand core of tempered steel wire on which several layers of steel music wire are wound alternately in right and left hand helices. See figure 10. The direction of pitch, whether right or left, of the final

helix is made such that it tends to coil tighter when the shaft is in use. The casing consists of an inner flexible steel tube and an outer one of whip cord braiding.

The tachometer shaft adopted as standard by the Army and Navy air services has a shaft diameter of 0.150 inch and an over-all diameter of the shaft casing of $\frac{3}{4}$ inch, and a specified design for the connections to the engine and to the tachometer. The standard for aircraft (not for marine use) adopted by the Society of Automotive Engineers (see S.A.E. Handbook) is the same except for slight differences in the end connections. Shafts according to either standard are interchangeable. The standard shaft as ordinarily constructed will transmit safely a torque of not more than 8 pound-inches when the shaft is straight and a torque decreasing from this value as the curvature is increased.

Steel driving elements and other steel parts become magnetized and in this condition are a source of troublesome error in the indications of the magnetic compass. For this reason nonmagnetic flexible shafting is very desirable and is under development.

The length of flexible shafts in service is limited to about 35 feet and rarely exceeds 25 feet. They must be installed without sharp bends; the radius of curvature should not be less than about 12 inches. Operation at low temperatures causes failure in many instances owing to the stiffening of the lubricant in the drive shaft casing and in the tachometer.

ELECTRIC TACHOMETERS

Tachometers of the electrical type developed for aircraft use consist either (a) of a voltage-generating element rotated by the engine through a very short connecting shaft and a distant indicator of this voltage or (b) of a commutator rotated by and at the engine and of some device either mechanical or electrical in nature for counting the number of electrical impulses per unit of time.

The electric tachometer is particularly suited, in contrast with the mechanical tachometer, for securing an indication on the instrument board of the speed of the outboard engines of multi-engined aircraft. There is also the possible advantage that two or more indicators may be connected to the same generator. However, the cost of the electrical type is greater than that of the mechanical tachometer of equal accuracy.

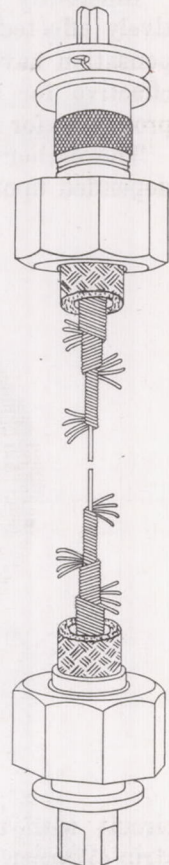


FIGURE 10. — Diagram of a flexible drive shaft.

A. DIRECT CURRENT TACHOMETERS

Essential parts.—This tachometer consists of a generator attached to the engine at the point usually provided for the tachometer connection, and a volt-

about 270° of arc. The indicator first mentioned is installed in a fan-shaped case (fig. 11) which is awkward to mount on an instrument panel, while the latter is in a case (fig. 12) the size and shape of which conforms to that adopted as standard for aircraft

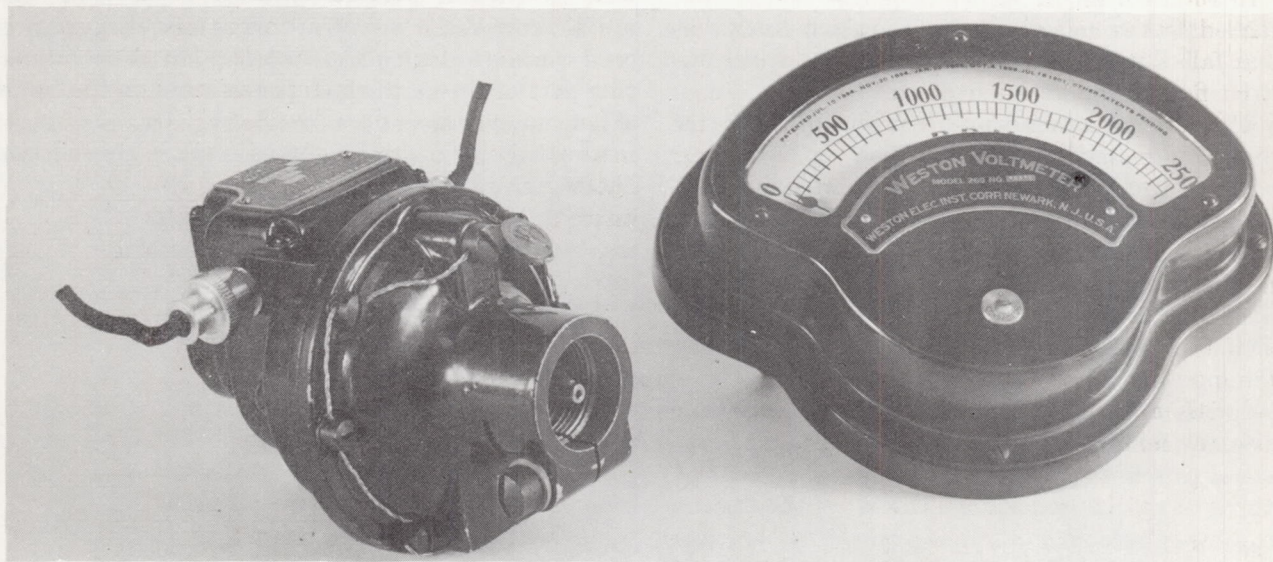


FIGURE 11.—Generator and fan type indicator of Weston d.c. electric tachometer.

meter of the moving coil type for indicating the speed. The field of the generator is obtained from a permanent magnet, usually of cobalt steel. The generator and

instruments. The fan-shaped indicator weighs 22 ounces, the other, 20 ounces. The generator develops 3 volts per 1,000 r.p.m. It weighs 20 ounces and is designed to fasten directly to the tachometer fitting of the engine. The instrument is furnished with both the generator and indicator individually compensated for temperature.

Tetco.—A photograph of the Tetco tachometer is shown in figure 13. The indicator of this instrument weighs 20 ounces, has a pointer deflection of 270° and conforms in size and shape to the new standard for the cases of aircraft instruments. The generator develops 4.5 volts per 1,000 r.p.m., weighs 18 ounces, and is designed to fasten directly to the tachometer fitting of the engine.

Horn.—The Horn electric tachometer shown in figure 14 is of German manufacture and is not particularly suitable for use on aircraft, as is evident from the fact that the magneto weighs $4\frac{3}{4}$ pounds. It develops 25.6 volts per 1,000 r.p.m. and is designed to be connected with the engine by means of a short length of flexible shafting. The indicator has a maximum deflection of the pointer of 300° , a resistance of approximately 2,400 ohms, and weighs 26 ounces.

Characteristics of d.c. tachometer.—In general the lag in indication of these instruments is negligible. Some difficulty is experienced in maintaining a given calibration due to a weakening with time of the permanent magnets in the generator and indicator, and to a zero shift of the hairspring in the indicator. These possible defects are well known and can be avoided by careful technique in manufacture.

the indicator are connected by means of two insulated electrical conductors.

Weston.—A photograph of the Weston tachometer is reproduced in figure 11. Either of two types of indicators are available for use with this instrument, one having a pointer deflection of 120° and the other

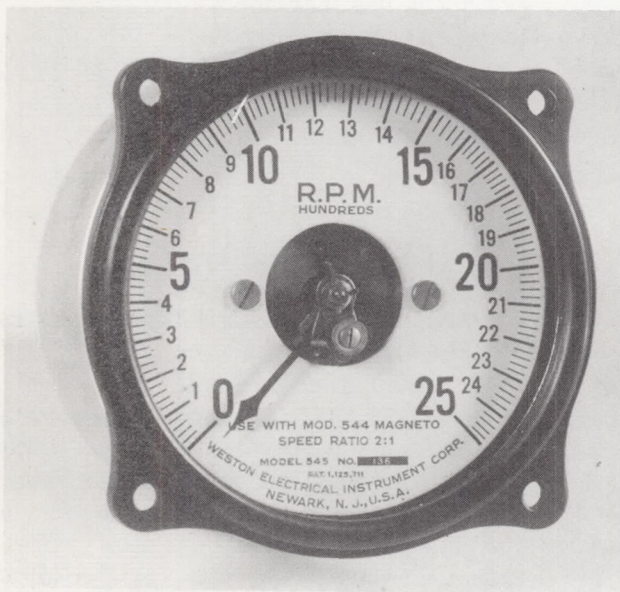


FIGURE 12.—Indicator of the Weston d.c. electric tachometer with 270° pointer motion.

The d.c. instrument has long been available, but has not been used extensively on aircraft until quite recently. In order to be satisfactory for such use the requirements special to such operation had to be met by modifications in existing designs. These are outlined below.

(a) *Weight.*—The general requirement of low weight for aircraft parts has led to the development of generators of light weight with essentially the same voltage output as that of heavier generators previously available. However, the weight of complete instruments at present available is inherently greater than that of mechanical tachometers. The difference is not so considerable when the weight of a long line of flexible shafting is included with that of the mechanical tachometer.

(b) *Long scale indicator.*—In order to conserve space on the instrument board and at the same time secure an adequate length of scale, an indicator with a much greater pointer motion is required than the 120° of arc of the ordinary fan type voltmeter. Several methods for increasing the range of pointer motion are now being employed. A sector and pinion mechanism is used in the indicator of the Horn tachometer shown in figure 14, by means of which an angular deflection of the pointer of about 300° is secured.

A pointer motion of approximately 270° of arc has been obtained in the cirscale indicator by a unique arrangement of the pole faces of the permanent magnet, one of which is split to permit the insertion of the pointer shaft and moving coil (reference 8). A diagram of the mechanism is shown in figure 15 and a photograph of a commercially manufactured instrument in figure 12. Securing the necessary scale length by a greater angular deflection of the pointer has obvious advantages. A disadvantage, however, of this indicator is its lack of sufficient ruggedness to endure the vibration to which it is ordinarily subjected on an instrument board.

(c) *Compensation for temperature.*—The indicator and the generator must be individually compensated for temperature, first, because of the range of temperature to which the instruments are subjected and second, because the temperature of the indicator on the instrument board may be widely different from that of the generator installed close to the engine. Compensation is necessary because of the effect of temperature on the resistance of the windings, on the permeability of the magnets of both the generator and indicator, and on the stiffness of the hairspring of the indicator (reference 2).

A commercial instrument was compensated at the Bureau of Standards in 1928 by the following method. The air gap of the permanent magnet of the generator was provided with a magnetic shunt of "thermalloy"

(reference 10). This material is a copper-nickel-iron alloy, the magnetic permeability of which is low compared with that of ferrous materials, and decreases almost linearly with increase in temperature. In the uncompensated generator the voltage decreases with rise in temperature which, in the generator provided with the thermalloy shunt, is prevented by an increase

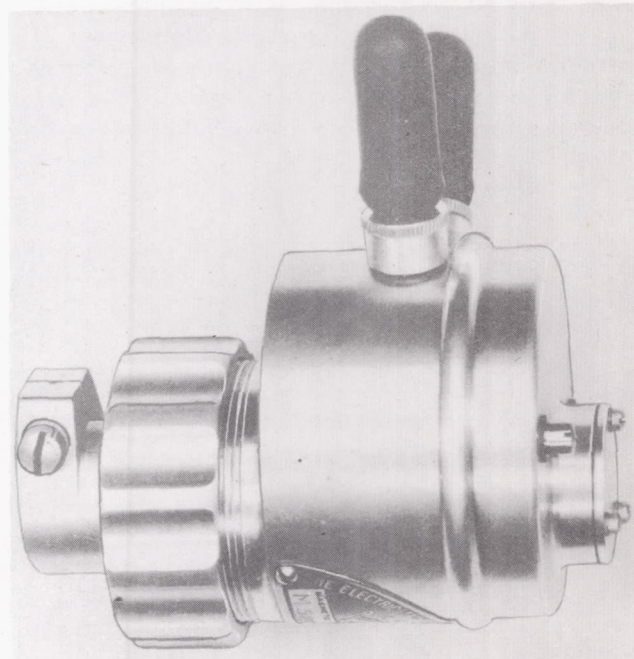
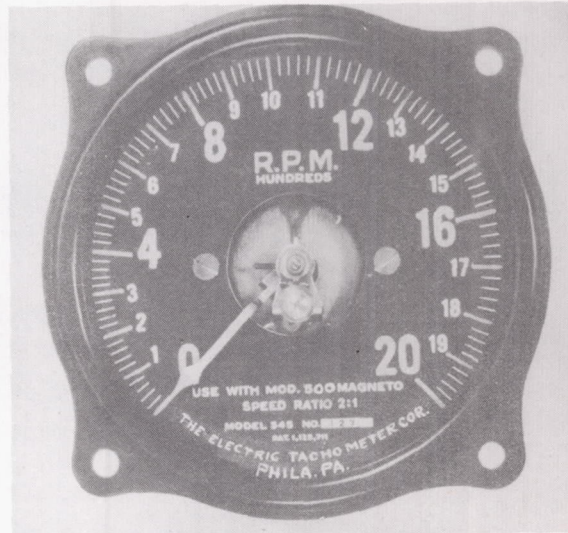


FIGURE 13.—Indicator and generator of Tetco d.c. electric tachometer.

in magnetic flux across the air gaps due to a decrease in flux across the shunt.

The temperature coefficient of the uncompensated indicator may be in general either positive or negative, depending upon the design. Compensation was affected in the indicator of the above-mentioned instrument by adding a series-parallel combination of electrical resistances of copper and constantan.

(d) *Rugged indicator.*—It is common experience that delicate electrical instruments will not withstand vibration of the severity found on instrument boards unless mounted in some sort of shock-absorbing ma-

B. ALTERNATING CURRENT TACHOMETER

This instrument consists of an alternating current generator and a suitable indicator. The field of the generator consists of one or more permanent magnets,

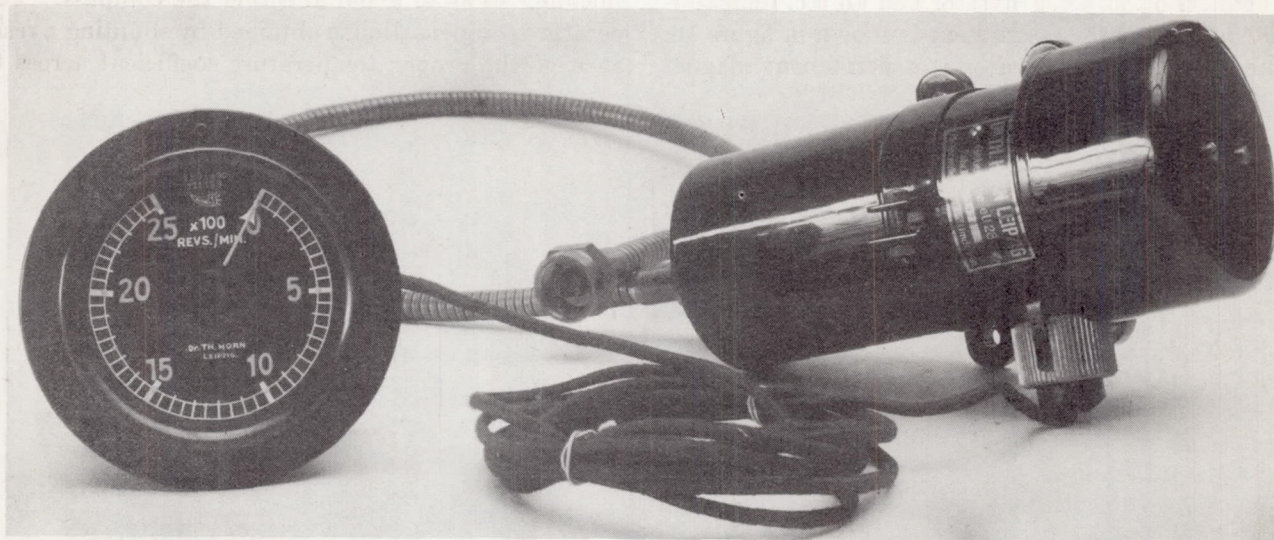


FIGURE 14.—Horn d.c. electric tachometer.

terial. In general, the ruggedness of an instrument of a given design decreases with its sensitivity. It is therefore important that the generator produce as large a voltage as possible consistent with low weight, not only to avoid the effect of variation in brush and

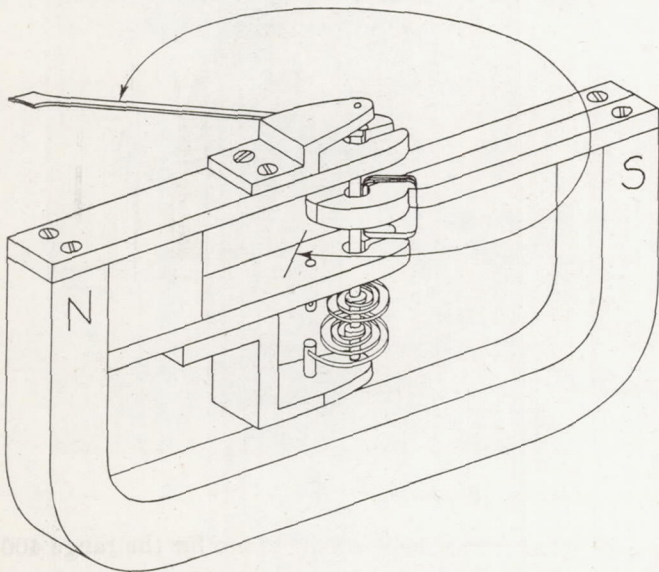


FIGURE 15.—Diagram of mechanism of Cirscale moving coil instrument.

commutator resistance but also to permit the use of a less sensitive indicator.

(e) *Magnetic shielding.*—The indicators of electrical tachometers usually contain permanent magnets, or electromagnets, which makes it essential to provide magnetic shielding in order to avoid an effect on the indications of magnetic compasses mounted in their proximity.

usually of cobalt steel. As the rotor of the generator revolves there is induced in the stator windings an alternating voltage the frequency of which is proportional to the speed of the engine. The windings of the stator may be connected to secure either 1-, 2-, or 3-phase current, depending upon the type of indicator used.

If the generator is of the single-phase type, the induced voltage is measured, after rectification by a copper oxide rectifier, by a direct current voltmeter calibrated in units of speed of rotation.

If the generator is of the 2-phase type, an indicator of the watt-hour-meter type is used, the disk of which is restrained from revolving by a hairspring so that its deflection becomes a measure of the speed.

When the windings of the generator are designed to secure 3-phase current, the drag induced by a rotating field in a metallic disk or cylinder (restrained from revolving by means of a hairspring) is used to indicate the speed. The rotating field in the indicator is secured by a stator, the windings of which are connected for 3-phase current.

General electric.—This instrument is of the single-phase type and consists of an a.c. generator, d.c. indicator, a saturation transformer, and a copper oxide rectifier. The saturation transformer gives a voltage output proportional to the frequency alone. The generator is of the polar inductor type and has stator windings which are coiled around a nonrotating, permanent magnet. A soft iron spider is the only rotating part. The indicator is supported within another case on a layer of sponge rubber so that it is shielded from the effects of severe vibration. The outer case con-

forms in dimensions to the standard 2 $\frac{3}{4}$ -inch dial size case. The total weight of the instrument is approximately 4 $\frac{1}{2}$ pounds.

Pioneer.—This instrument is of the 2-phase type and consists of an a.c. generator and an a.c. indicator. A photograph of the instrument is shown in figure 16.

The rotor of the generator is a permanent magnet

about its axis against the torque of a hairspring. A pointer on the disk shaft indicates its position relative to the dial. Damping of the disk is obtained by means of a permanent magnet, the use of which requires shielding so as to avoid affecting the compass. Temperature compensation is obtained by shunting a resistance of the proper temperature coefficient across the

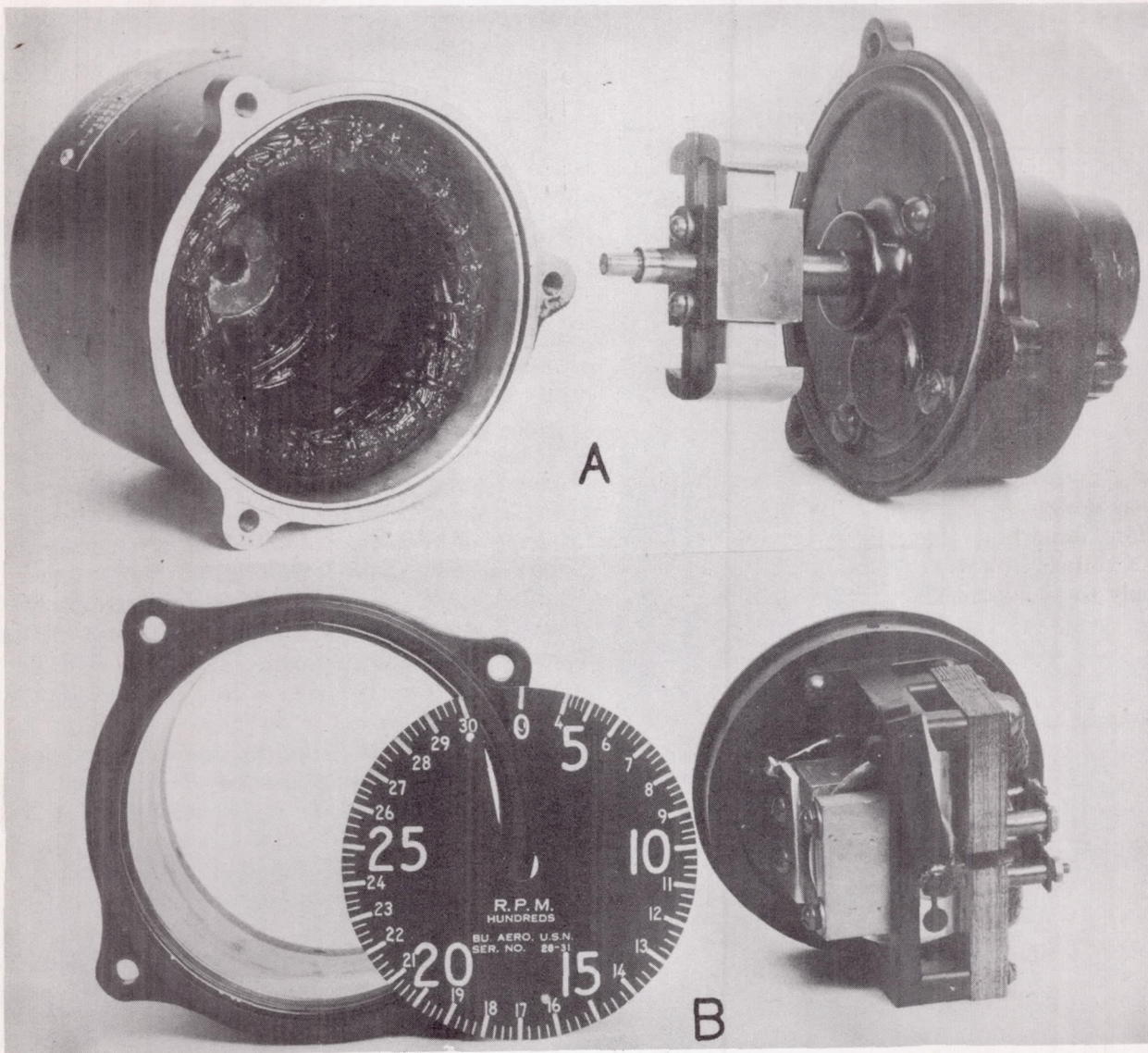


FIGURE 16.—Pioneer a.c. electric tachometer. A, generator; B, indicator.

and the stator is of the 2-phase 3-wire, wound type. A swamping resistance is added so as to obtain an indication independent of the usual variation in the length of leads used in service. Temperature compensation is obtained by means of a magnetic shunt. The rotor makes 13,500 r.p.m. when the generator is connected to a shaft having a speed of 1,500 r.p.m.

The indicator contains two stationary coils electrically connected to the output side of the generator. The revolving magnetic field thus set up produces eddy currents in an aluminum disk which is free to turn

coils. The pointer moves 345° of arc for the range 400 to 3,000 r.p.m.

The weights of the generator and the indicator are 2.4 and 1.2 pounds respectively.

Comparative advantages and disadvantages.—The principal advantage of the alternating current tachometer lies in the elimination of the errors caused by variation in the resistance between the commutator and the brushes. The alternating current tachometer, however, has the disadvantage of weighing more than the direct current instrument.

C. SOLENOID-OPERATED CHRONOMETRIC TACHOMETERS

Stover-Lang.—The Stover-Lang tachometer, as developed for aircraft use, consists of a chronometric tachometer, a solenoid, an electric contactor, and a battery of 12 volts or other source of direct current. The solenoid is mounted within the indicator and the contactor is fastened to the tachometer adapter of the engine. The battery, electric contactor, and solenoid

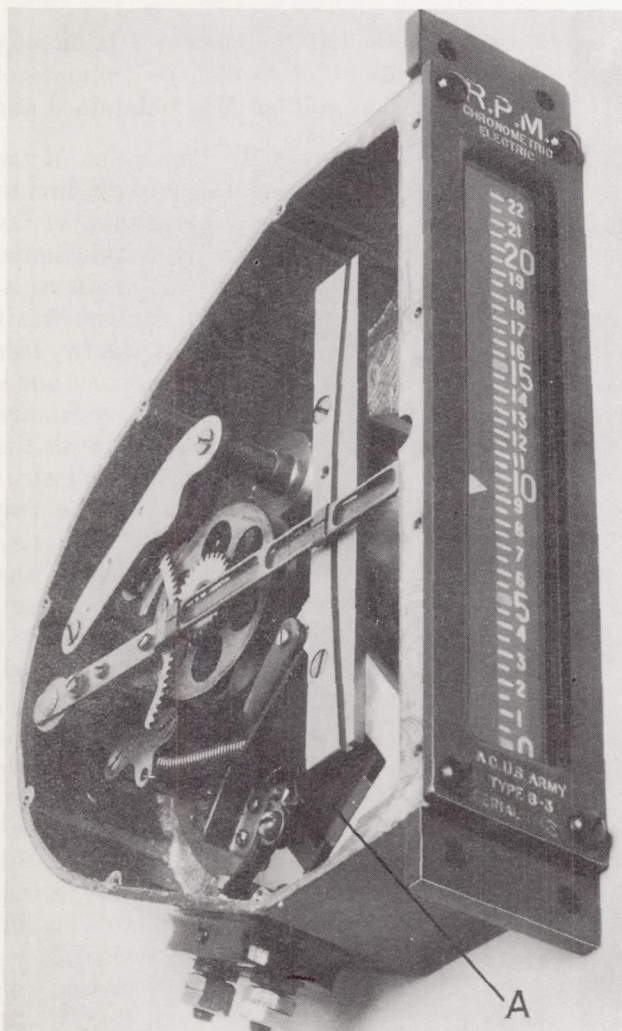


FIGURE 17.—Stover Lang chronometric-electric tachometer.

are connected in series. A photograph of the indicator of this instrument is shown in figure 17, in which A is the solenoid. For aircraft use the indicator has been developed only in the vertical-scale type. The contact in the contactor unit is made and broken by means of a cam, which is rotated by the engine. During each revolution of the cam of the contactor (two revolutions of the engine crankshaft) the circuit is opened and closed two times, and thus intermittently energizes the solenoid in the indicator. The solenoid operates a pawl and ratchet mechanism which

drives the chronometric tachometer at a rate proportional to the speed of the engine.

Comparative advantages and disadvantages.—The instrument suffers in comparison with the d.c. and a.c. tachometers in that (a) an outside source of current is required, (b) it is an integrating instrument and thus in general has inherent defects of a relatively long period between indications and of not indicating the instantaneous speed. To avoid the possibility of draining the battery, it is essential that the electrical circuit be broken when the instrument is not in use. Up to the present (1932) the cost of this instrument has been greater than that of the d.c. or a.c. types.

This instrument compares favorably with the d.c. and a.c. types in that (a) a sufficiently long scale can be obtained without loss of ruggedness or accuracy. Although the instrument is available only in the vertical scale type, there is no inherent difficulty in modifying it for installation in a round dial type case and in securing a pointer motion of one revolution or greater. (b) The indication is independent of changes in the temperature of the mechanism, provided that a lubricant of the proper grade is used and that the escapement is compensated, which is a well-understood and common procedure. (c) The accuracy is ordinarily maintained for the operating life of the instrument, while with the direct or alternating current tachometers there is possibility of changes in the magnetism of the permanent magnet and the effect of mechanical wear in the generators and indicators. (d) The scale is inherently evenly divided in speed units as contrasted with some of the designs of a.c. instruments.

In common with the chronometric types the instrument is easily adjusted to a desired calibration by varying the periodicity of the escapement. There is no position error.

On the whole the inherent disadvantages of the instrument preclude its extensive use.

D. COMMUTATOR-CONDENSER TACHOMETERS

Principle of operation.—In this instrument an electrical condenser is alternately charged and discharged at a rate proportional to the rotational speed which is to be measured.

A number of electrical circuits, of which one of the most efficient will be described, have been devised to utilize this principle (reference 36). The essential parts consist of a commutator A (fig. 18) designed for attachment to the engine at the tachometer connection, an electrical condenser B of fixed capacity, a milliammeter C (graduated in r.p.m.), and a source of direct current D. The part of the circuit marked E in figure 18 is a voltage regulator which will be discussed later. Each terminal of the condenser is

connected to alternate segments of the commutator through a slip ring. As the commutator is rotated from one segment to next, the condenser is discharged and again charged with electricity of the opposite sign, all of which quantity of charge passes through the milliammeter C.

The indication depends upon the voltage impressed upon the condenser. This voltage is measured by the milliammeter C upon completing the circuit through resistance G by means of switch F (fig. 18).

Theory.—Neglecting the inductance in the circuit shown in figure 18, which is largely that of the moving coil of the indicator, the charge passing through the indicator during the time the brushes remain in contact

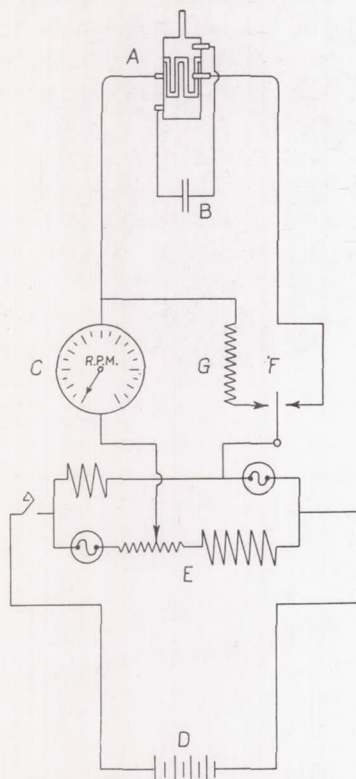


FIGURE 18.—Electric circuit of commutator-condenser type tachometer.

with a given segment of the commutator is given by the expression:

$$Q = CE \left(1 - e^{-\frac{t}{Cr}} \right) \quad (9)$$

Here Q is the charge transferred in the circuit in the time t , C is capacity of the condenser, r is the resistance in the circuit, and E is the voltage applied at the instant from which time t starts. If t is the time interval of contact on the commutator, Q is the charge passing through the indicator per contact. It should be noted that the effective voltage E applied to the condenser is twice the voltage output from the voltage regulator as the polarity of the condenser is changed from complete charge for one direction to complete charge in the opposite direction of flow.

The total charge passing through the indicator per second, or the current I is

$$I = NQ \quad (10)$$

where N is the product of the number of commutator segments and the rate of rotation. Substituting for Q from equation (9) it is seen that

$$I = CEN \left(1 - e^{-\frac{t}{Cr}} \right) \quad (11)$$

This equation shows that the current I is directly proportional to the rate of rotation of the commutator provided that a constant voltage E is maintained and that the quantity $e^{-\frac{t}{Cr}}$ be small. The value of the latter quantity depends upon the design of the circuit, and its constancy upon keeping the variation of the brush-commutator resistance within reasonable limits.

Automatic voltage regulator.—The automatic voltage regulator (reference 1) consists of a parallel circuit of equal resistances (E , fig. 18), both of the two legs of the circuit being composed of a fixed resistance and a tungsten lamp but in reversed order. The resistance of the tungsten lamps varies approximately with the impressed voltage. The output voltage for the instrument is taken from the junction point of the two resistances in each leg of the circuit. Its constancy depends upon the characteristics of the lamps, the current required and the variation in the voltage supplied. In one circuit the output voltage remained constant within 0.3 percent for values of the voltage supplied from 10.5 to 13.5 volts. The efficiency, defined as the power output divided by power input, is very low in the circuits thus far devised, not exceeding 2 percent.

Instruments constructed.—These instruments have not been used extensively in aircraft for measuring the speed of the engine. A tachometer of this type was constructed in 1921 at the Bureau of Standards for the Army Air Service (reference 34). The electrical circuit differs from that described (fig. 18) in that the differential voltage on the condenser was that of the supply battery and not twice its value.

Instruments operating on this principle are used to measure the air speed of airships in which case the commutator has been driven by a propeller or in one case by Robinson cups (reference 20).

Advantages and disadvantages.—The commutator-condenser tachometer is not excessive in size and is relatively light in weight. The lag in indication is negligible and aircraft accelerations have comparatively little effect on its indications. It is easily compensated for temperature errors. On the other hand there is the necessity for an external source of direct current, the necessity for operating a switch when the instrument is not in use if a voltage regulator

is used, and the difficulty of securing satisfactory performance from the inherently sensitive indicator when it is subject to airplane vibration. Its simplicity of design and other characteristics render this instrument of possible use on multi-engined aircraft.

STROBOSCOPIC TACHOMETER

This instrument consists of two parts, a device for interrupting at an adjustable rate the rays of light reflected from a propeller, or other rotating part, and

rotate the distance between two of the holes. The speed of the propeller is obtained from the following equation,

$$S = Nh$$

where S is the speed of the propeller, N the speed of the disk, and h the number of holes in the disk.

Many forms of stroboscopic instruments have been developed (references 32, 33, 35, 40, 42, 43, and 44).

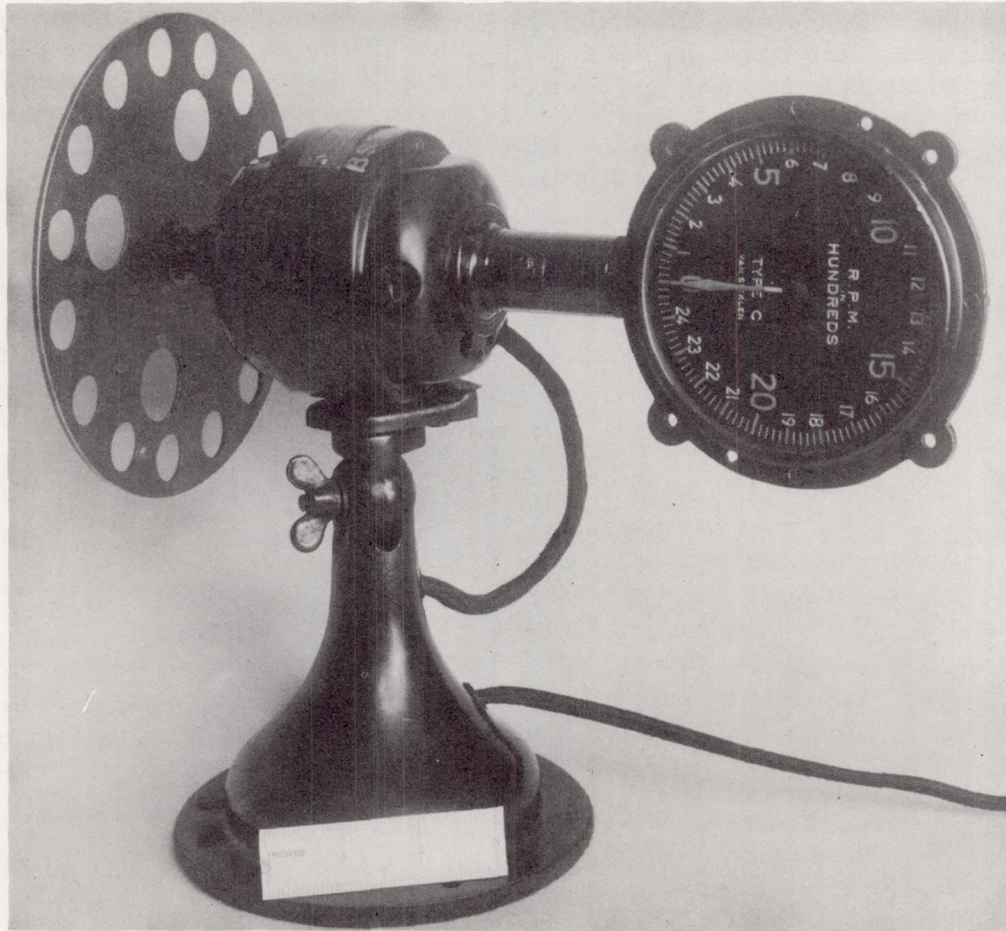


FIGURE 19.—Stroboscopic tachometer.

a tachometer. Figure 19 shows a simple form of stroboscopic tachometer utilizing a small fan motor. In this apparatus a motor-driven disk, in which uniformly spaced holes were drilled on a circle concentric with the disk, serves as the interrupter. The speed of the disk is controlled by a rheostat mounted within the base of the motor and is indicated by the tachometer connected to the opposite end of the shaft.

If all of the blades of the propeller except one have been blackened and the speed of the tachometer is adjusted so that the image of the propeller, as seen through the holes of the stroboscopic disk, appears to remain stationary, then the propeller makes one complete revolution in the time required for the disk to

The stroboscopic tachometer is useful in determining the speed of any revolving object to which it is inconvenient or undesirable to connect mechanically a tachometer. It has been used on lighter-than-aircraft of the larger size as a means for determining at a central point the speed of the individual propellers.

MISCELLANEOUS TACHOMETERS

Two instruments, the pneumatic and the resonance, have thus far not come into any extended use on aircraft, but may have future possibilities.

A. PNEUMATIC TACHOMETERS

The pneumatic tachometer consists of an air pump and a pressure gage. The pump is attached directly

to the tachometer adapter and develops a pressure depending upon the speed of the engine. It is connected by means of copper tubing with a pressure gage which is graduated in speed units.

The pneumatic method of measuring rotational speeds has been used to some extent in automotive service (Van Sicklen speedometer, reference 5) in which form the pump was contained within the case of the pressure gage and was driven by a flexible drive shaft. New designs, however, have recently been developed abroad.

Askania.—As shown schematically in figure 20, this instrument as designed for aircraft use has two units, consisting of (a) a centrifugal element and an air pump, attached to the tachometer adapter of the engine, and (b) of an indicator installed in the cockpit. The indicator and engine unit are connected by means of a length of air tight metallic tubing. The centrifugal element A controls the position of piston B operating in a cylinder provided with ports located at one point along its axis. As the centrifugal element is revolved by the engine it moves the piston so as to cover the port openings. The pressure of the air delivered by the pump to the cylinder thus closed off is sufficient to overbalance the centrifugal force and to move the piston back so as to open the ports sufficiently to relieve the air pressure in excess of that needed for balancing. The pressure of the air required to balance the piston varies with the speed of rotation of the centrifugal element and is measured by the indicating instrument. Since large port openings are uncovered by a small displacement of the piston the position of the latter is essentially constant at all speeds, and therefore the balancing pressure depends only on the speed.

The weight of the pump unit of the Askania pneumatic tachometer is approximately 22 ounces.

Amyot-Le Prieur.—This instrument consists of an oleo centrifugal pump and a pressure gage. The pump is mounted on the engine and is driven by a short length of flexible shafting. In one form of the instrument the air above the oil in the pump is compressed an amount depending upon the speed of the rotor. The pressure is then transmitted pneumatically through copper tubing to the indicator, which is graduated in terms of the speed of the engine. In another form, the pump when operating is entirely filled with oil and a line filled partly with air and partly with oil connects the pump with the indicator.

Neither form of the instrument appears to give satisfactory performance owing to the effect of pitch of the aircraft on the indication of the oil-filled instrument and the effect of temperature on the pneumatic transmission type.

B. RESONANCE TACHOMETERS

Resonance tachometers (reference 24) have not been developed for aircraft, but may possibly be of use in measuring engine speed in view of the fact that instrument boards in most airplanes with a single engine vibrate with the same frequency as the engine. The instrument contains a graduated series of tuned metal reeds, the natural frequencies of which vary uniformly in the range of the instrument. When the instrument is brought into contact with the frame of a vibrating or rotating body at any given frequency of vibration, or rate of rotation with even slight unbalance, one or a group of the reeds vibrates in resonance, and thus indicates the input frequency. Extraneous vibrations

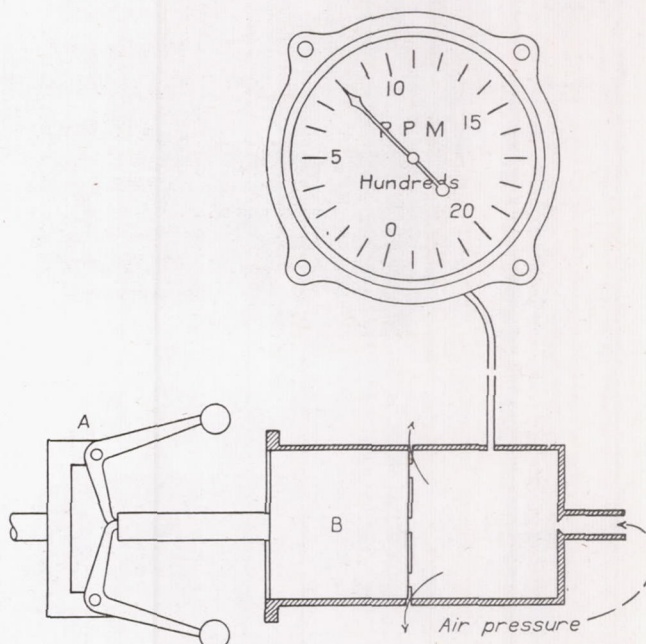


FIGURE 20.—Diagram of Askania pneumatic tachometer.

and harmonics of the fundamental frequency may cause ambiguity in the indications.

LABORATORY TESTING OF TACHOMETERS

A. APPARATUS

It is more convenient in practically all cases to determine the errors of tachometers by means of laboratory tests. The calibration apparatus consists of a standard instrument and means for driving at variable speeds both the standard and the tachometer under test.

Calibration apparatus—(a) With d.c. motor.—The tachometer calibration apparatus used at the Bureau of Standards is shown in figure 21. A liquid centrifugal tachometer, T in the figure, is used as the master instrument. The instrument under test is connected

to the apparatus through the chuck *C*. A quarter horsepower direct-current motor having a rated speed of 1,160 r.p.m. at full load is used to operate the instruments. The flywheel shown in the figure serves the twofold purpose of preventing rapid fluctuations of the speed and of supplying a convenient means of regulating the speed which is accomplished by a pressure of the hand on the rim. A rheostat *R* mounted on the base of the apparatus forms part of the electrical circuit of the motor and is used to obtain a coarse adjustment of the speed. Switches are provided (a)

spring to absorb the jars incident to a gear-driven operating device. It has been found that centrifugal tachometers, which are the most susceptible to unevenness in operation of the driving shaft, may be operated with this device without any perceptible flicker of the pointers. It should be pointed out that when tests at low temperatures are made a lubricant must be chosen which in the temperature range remains in the liquid state.

(b) *With a.c. motor.*—If an a.c. motor is used to drive the test apparatus, the speeds at the various test

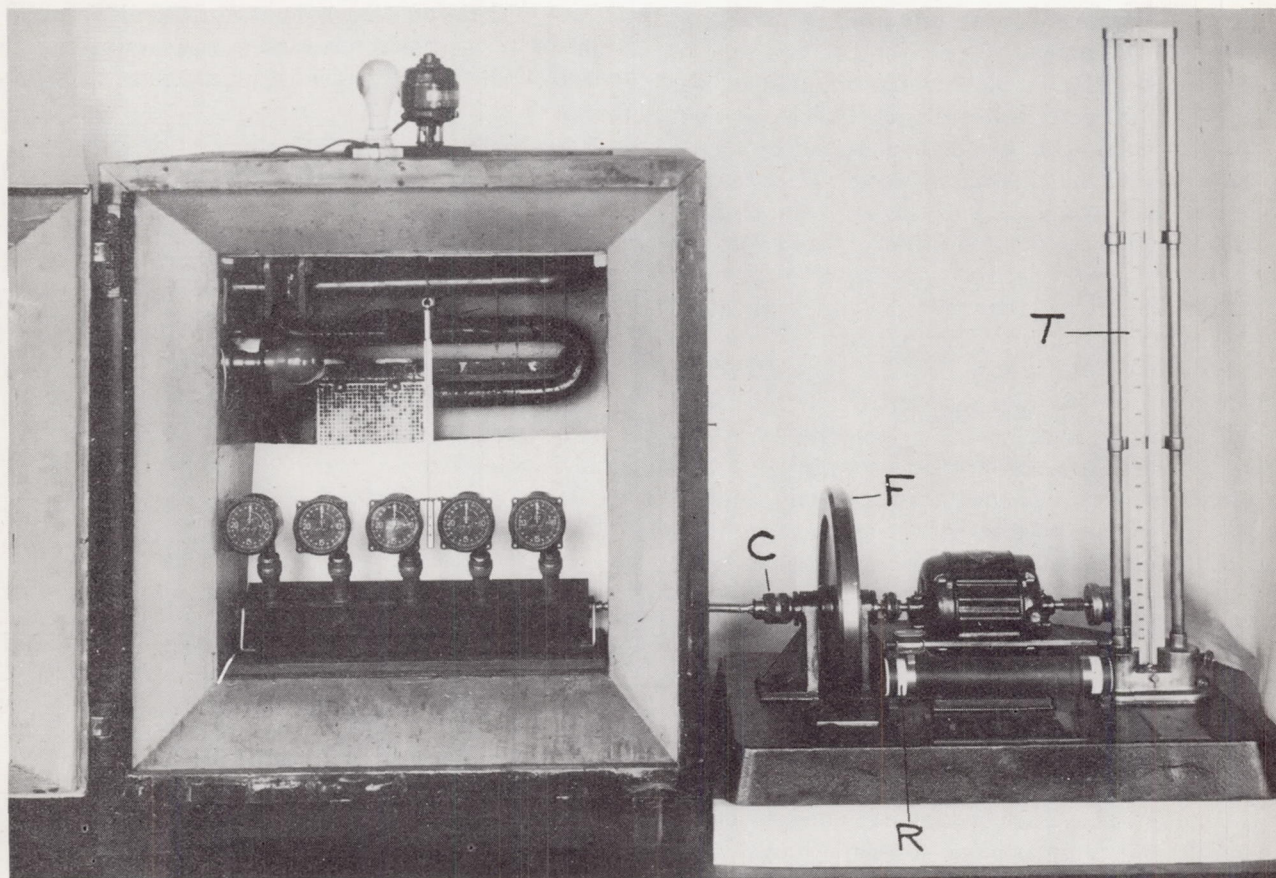


FIGURE 21.—Tachometer test stand and temperature control chamber.

between the motor and the power supply, (b) for reversing the direction of rotation of the motor, and (c) for inserting the rheostat either in the armature or field circuit of the motor. The instrument drive shafts are connected to the motor shaft through flexible couplings. See reference 30 for a more detailed description.

A test stand such as shown in figure 21 is used when it is desired to test more than one instrument at a time. The stand consists of a horizontal main shaft which is directly connected with the driving motor and five vertical counter shafts which are coupled to the main shaft by means of spiral bevel gearing. These parts are all enclosed in an oil-tight housing. Each tachometer is driven through a flexible helical

points must be obtained by mechanical means since the motor speed cannot be sufficiently varied. The main drive shaft of the tachometers and the master instrument is connected to the motor shaft by a friction disk and wheel. The variation in the speed of the instruments is obtained by varying the point of contact of the wheel along the radius of the disk.

A cone can be used instead of the disk, the wheel being arranged to make contact at any desired radius of the cone. This gives a much closer speed adjustment.

In some cases tests are desired only at a few fixed speeds. In such cases a gear box arranged so as to have outlets rotating at the desired speeds has been found to be more convenient than the use of the friction disk.

(c) *With motor-generator set.*—With only alternating current available there is the alternative possibility of obtaining variable speed by using an a.c. motor-d.c. generator set which may be preferable to the use of the friction disk and wheel described above. Two generators would give the ideal solution, one to maintain constant voltage on the field of the driving motor and the other to furnish a variable voltage on its armature. This variable voltage can be obtained by adjusting a rheostat connected in series with the field of the generator.

(d) *With synchronous motor.*—In calibrating instruments at a factory it is in some cases advantageous to use a synchronous motor to drive the tachometers. In order to obtain the chief advantage of this type of apparatus which is the elimination of the master tachometer, it is necessary that the frequency of the electric current be controlled at the source so that the fluctuations in speed are within desired tolerances. A gear box is used to obtain a number of values of the speed within the range of the tachometers to be adjusted so that each outlet of the gear box can be used as the source of a definite constant speed. A distinct limitation of the apparatus is the fact that only a limited number of speeds can be obtained.

Liquid veeeder master tachometer.—The master tachometer (T, fig. 21) is essentially a liquid centrifugal pump. The pressure developed is measured by a manometer in which the liquid customarily used is kerosene colored red with an aniline dye. The rotor of the pump, which is at all times completely immersed in the liquid, is equipped with radial blades and is mounted in its housing with small clearances. The use of radial blades obviously enables the instrument to hold its calibration for either direction of rotation of the pump. The instrument is provided with two knobs, one for adjusting the height of the liquid in the reservoir to the proper level and the other for adjusting the damping of the liquid column. The first adjustment is obtained by raising or lowering a partly submerged sink in the reservoir. The second adjustment is produced by controlling the area of a restriction at the entrance to the manometer tube.

The pressure developed in the liquid due to centrifugal force at any point along the axis of rotation is

$$dP = w^2 D r dr \quad (12)$$

Where P is the pressure developed,

w is the angular velocity,

r is the radius of rotation at the point at which

P is measured,

and D is the density of the liquid.

In the instrument the pressure caused by centrifugal force is balanced by a head of liquid in the manometer tube so that

$$P = g D h$$

where h is the head of liquid and g is the acceleration of gravity.

It follows that

$$dh = \frac{w^2 r dr}{g} \quad (13)$$

Integrating both sides of this equation we have

$$h = \frac{w^2 R^2}{2g} + c \quad (14)$$

where c is the constant of integration and R is the radius of the radial blades.

Since $h = 0$ when $w = 0$, $c = 0$ and it follows that

$$h = \frac{w^2 R^2}{2g} \quad (15)$$

It is obvious from this equation that the scale of a manometer calibrated in speed units is unequally divided, being progressively more open from low to high speed. The scale of an instrument having a range of 1,500 r.p.m. and a scale 36 inches long is rarely graduated in the range from 0 to 250 r.p.m.

For testing service instruments it has been found convenient to have the master tachometer equipped with two scales, one graduated to indicate the speed, and the other twice the speed. The latter scale is used when testing aircraft tachometers which are operated in service by the cam shaft (one half the speed of the crankshaft). Gear boxes are used either between the master tachometer and the driving motor shaft or between the instrument under test and the driving motor shaft, in order to drive the instrument under test at the proper speeds and at the same time to obtain indications on the sensitive part of the scale of the master instrument.

Methods of testing master tachometers.—(a) *Revolution counter and clock.*—A fundamental method of calibrating master tachometers consists of counting the number of revolutions for a measured period of time while the speed is maintained constant. The revolutions per unit time give the speed. This method is simple and requires no special or expensive apparatus. A stop watch, or a watch with a second's hand, and a revolution counter comprise the needed apparatus.

The sources of the largest error are in the difficulty of making the observations and in holding the speed of the master instrument constant.

(b) *Semiautomatic timing apparatus.*—A semiautomatic apparatus is used at the Bureau of Standards for determining the total number of revolutions in a given time interval. It has the advantage of eliminating in large measure the errors due to the personal equation.

The apparatus consists of a bicycle counter, a clutch, two solenoids, and a relay. A diagram of the electrical connections is shown in figure 22 and a photograph of

the apparatus in figure 23. Contact **A**, figure 22, is controlled by the relay **R** which is actuated by the time signals from a master clock. Switches **B** and **C** are hand operated by means of push buttons. When contacts **A** and **B** are made, solenoid **S₁** is energized attracting lever **D**, and thus causing clutch **L** to engage the shaft **M** of the master tachometer. The counter is then recording the number of revolutions of the shaft

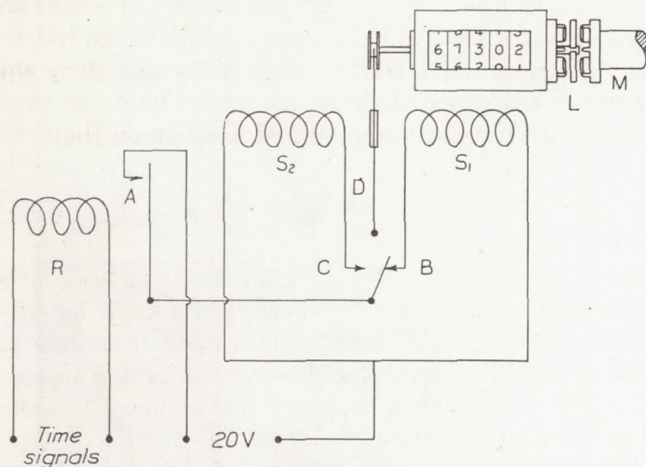


FIGURE 22.—Diagram of the apparatus used to calibrate the master tachometer.

M. When contacts **A** and **C** are made, lever **D** is pulled from a position in contact with solenoid **S₁** toward solenoid **S₂**, which disengages the clutch at **L**.

The signals from the master clock are received every second, except the fifty-ninth second, of each minute. This makes 1 minute a convenient timing interval. Just before the sixtieth second signal, the observer makes the contact at **B** until the clutch is engaged by the following time signal. One minute later, just before the sixtieth second, he makes the contact at **C** and the clutch is disengaged by the sixtieth second signal. The difference in the two readings of the counter gives the speed in revolutions per minute, it being assumed, of course, that the speed of the master tachometer has been held constant during the time interval.

In order that no coasting or slipping of the revolution counter exist either when being connected with, or disconnected from, the main shaft of the calibrating apparatus the revolution counter spindle is equipped with a fly which engages either the fins attached to the main shaft of the calibrating apparatus or to the revolution counter housing. The fins are designed so that a maximum error of 0.1 revolution may result when either connecting or disconnecting the counter. A total error of 0.2 revolution may therefore occur in the determination of the speed. The speed of the master tachometer calibrating apparatus cannot be adjusted to a constant value with an error less than one revolution per minute, so that the accuracy of the method of calibration is commensurate with that of the apparatus used for the purpose.

(c) *Speed indicator.*—In many cases a speed indicator of the chronometric type is adequate for determining the errors of a master tachometer. It consists of a timing element or escapement, a revolution indicator, and a mechanism whereby the revolution indicator is connected to the rotating spindle of the instrument for a definite interval of time, which is usually between 3 and 6 seconds. The deflection of the pointer is thus proportional to the number of revolutions for this time interval. The error of these instruments does not ordinarily exceed 0.3 percent. One instrument of this type weighs 5 ounces and is 2 inches in diameter and less than 1 inch in depth.

Field test set.—An inexpensive and simple apparatus is required for testing tachometers at airports and other field service stations. A simple form of apparatus which has proven suitable is that consisting of the mechanism of a hand-driven high-speed grinding wheel in which a small flywheel has been substituted for the grinding wheel. A chronometric or other tachometer of good quality, the errors of which are small or known, is mounted on the spindle shaft and serves as the master instrument. The tachometer to be tested is connected with the same shaft by means of a two-way adapter.

Temperature control apparatus.—The apparatus used at the Bureau of Standards for controlling the temperature of tachometers and other instruments consists of an insulated chamber in which the instruments are installed and which is designed so that suitable

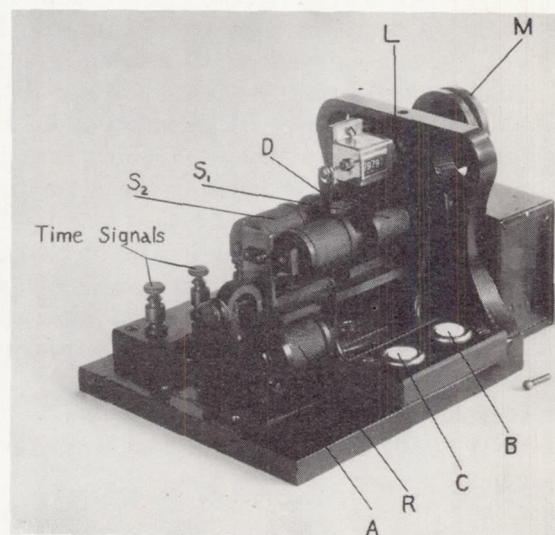


FIGURE 23.—Apparatus used to calibrate the master tachometer.

connections can be inserted through its walls to permit the master instrument to remain outside at room temperature. See figure 21. The chamber is conveniently heated above room temperature by means of an electrical heater which is thermostatically controlled. Temperatures below room temperature are obtained by means of an ammonia-refrigeration system. The apparatus is designed so that the ammonia is expanded

directly into coils located within the chamber itself. In order to obtain more quickly the temperature of -35°C . within the chamber, which is standard for routine tests, as well as to obtain the somewhat lower temperatures which may be required for special tests, a rotary compressor is installed to operate on the low pressure side of the ammonia compressor. The arrangement is such that the operation is either one or two stage as desired. It has been found that temperatures of -40°C . can be obtained easily with both compressors of the system operating simultaneously.

A temperature chamber in which solid carbon dioxide (dry ice) is used as a refrigerant is both convenient

between the bearings. One end of the shaft is cut to form an eccentric. An aluminum plate is mounted normal to the axis of the shaft and connected with its eccentric by means of a ball bearing. Parallel ball-bearing guides located at the four corners of this plate restrict its motion to one of reciprocation in its own plane and along the ordinate of displacement. The outer races of the guides are mounted on an intermediate aluminum plate, at the four corners of which are again located parallel ball-bearing guides which restrict its motion to one of reciprocation in its own plane and along the abscissa of displacement. The outer races of the latter guides are mounted directly on the brass

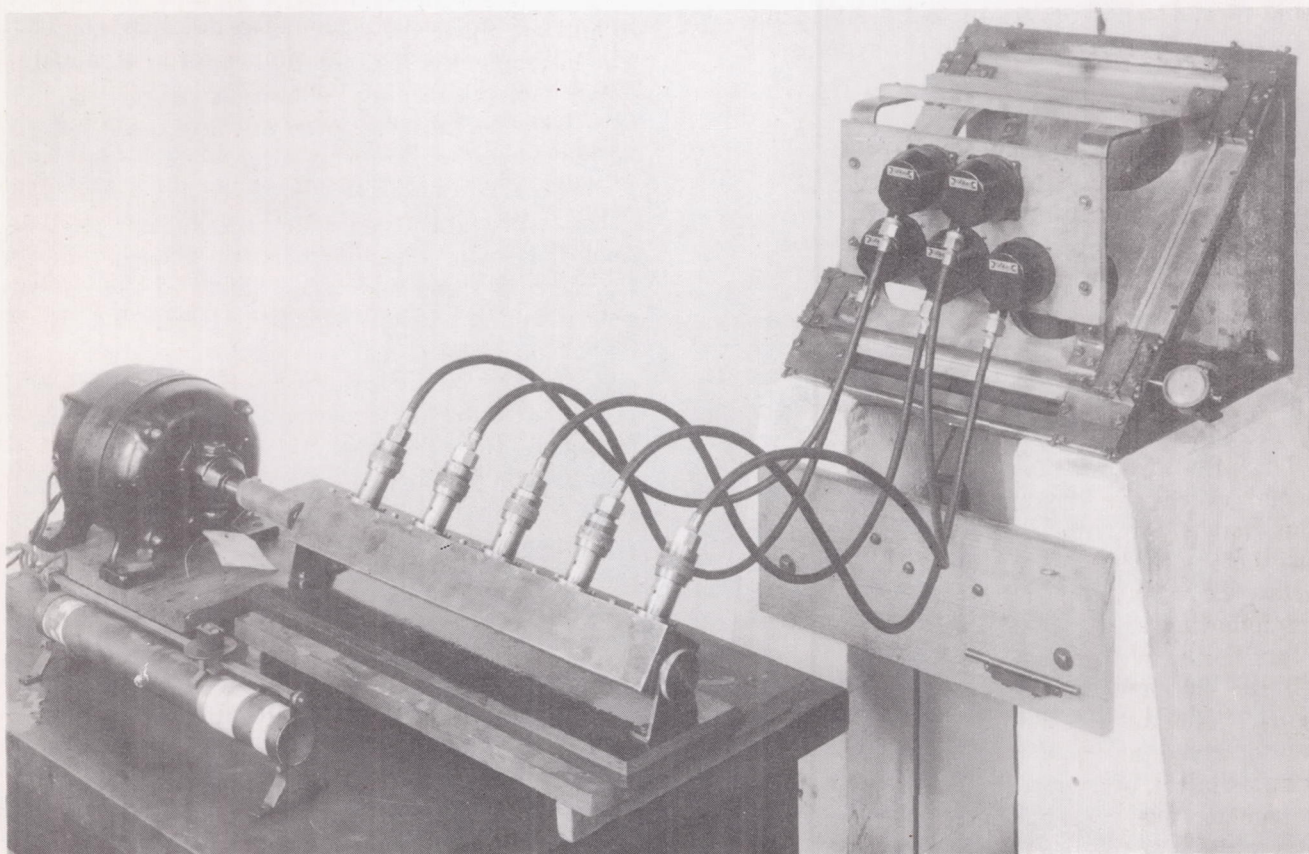


FIGURE 24.—Vibration board for testing aircraft instruments. Five centrifugal tachometers are shown under test.

and economical in many cases. Such chambers are used at Wright Field for testing aircraft instruments. See reference 20 for details.

Vibration apparatus.—The standard vibration to which aircraft instruments are subjected in the laboratory is a translational motion in a circular path one thirty-second inch in diameter in a plane inclined 45° with the horizontal plane. The frequency range of the vibration is from 1,000 to 2,000 cycles per minute.

The apparatus constructed at the Bureau of Standards for subjecting instruments to this standard vibration consists of a brass supporting frame (see fig. 24) in which a shaft is mounted on ball bearings. The shaft is rotated by means of a belt and pulley mounted be-

supporting frame which is designed to support the plate in the plane inclined 45° to the horizontal. The instruments under test are mounted with the plane of the dials vertical on a bracket attached to the first-mentioned plate of the vibration board. The equipment is arranged so as to secure any desired scale reading of the instrument undergoing vibration.

Speed acceleration apparatus.—An apparatus is required by means of which the instrument can be brought a selected number of times to a definite speed in 1 second. The apparatus used at the Bureau of Standards consists of an electric motor of sufficient power to bring the tachometer up to the selected speed in 1 second and a rotary switch which by

means of electrical signals from a standard clock periodically operates the motor. The use of this automatic switch is justified by reason of its greater convenience.

B. METHODS OF TEST

The nature of the tests made at the Bureau of Standards and the sequence with which they are made have been arranged in order that, first, the conditions encountered in service are simulated as nearly as possible; and second, the effect of any preceding test does not influence the results of the tests that follow. In general, but with some modifications and additions to suit the individual requirements of the various types of tachometers, tests are made for the following factors in the order given:

Factor	Test
Scale errors at room temperature (+20° C.)	Scale error test.
Lag in indication	Lag test.
Friction in the mechanism	Friction test.
Static balance of the mechanism	Position error test.
Effect of vibration	Vibration test.
Effect of exceeding the range of the instrument.	Overspeed test.
Temperature effects	Temperature tests.
Seasoning and speed acceleration effects.	Speed acceleration test.
Endurance	Endurance test.
Effect of electrical indicator on compass.	Shielding test.

These tests are substantially the same as those required for acceptance in the purchase specifications issued individually and jointly by the Army Air Corps and the Bureau of Aeronautics of the Navy Department. In these specifications the tests are conveniently divided into three classes—individual tests, routine type tests, and special type tests. The individual tests are made on each instrument and include the scale error and friction tests. The routine type tests include, in addition to the individual tests, the vibration, overspeed, and temperature tests, and are made on not less than 5 percent of the instruments of a given lot, selected at random. It is assumed that the performance of the instruments chosen for the tests is representative of the performance of all of the instruments of the lot. The position error, acceleration, and endurance tests are designated as special type tests, and are made, in addition to the individual and routine type tests, on a small number of instruments of a new design. The special type tests are made to determine that part of the performance which is a function of the design of an instrument and not carelessness in adjustment.

Scale error test.—In the manufacture of instruments in quantity lots the dials are usually standardized so that the spacing of the graduations is uniform. The mechanism of each instrument must therefore

be adjusted so that the deflection of the pointer of the instrument for a given speed is that required by the corresponding graduations on the dial. The error in indication is designated the scale error. The difficulty of avoiding scale errors is more fully appreciated when it is realized that the deflection of the sensitive element in many cases does not depend directly upon the quantity measured.

In the scale error test the tachometer at room temperature (+20° C.) is connected to the master tachometer. The readings of the two instruments are obtained at any desired number of points in the range with the speed increasing up to the highest speed of the range. In careful tests the instrument is brought up to but not above the speed at the desired test point. The instrument is then lightly tapped or vibrated just before taking a reading. The scale error is the difference between the true speed and the speed indicated by the instrument, and is positive when the instrument reads high, and negative when low.

Lag.—Instruments in which the indications depend upon the elastic elements in general differ in indication for increasing and decreasing values of the measured quantity. In pressure-measuring instruments the difference, in a special sense, is called the elastic hysteresis or lag. This difference in indication is also present in tachometers, but is in part due to mechanical imperfections in the mechanism.

In testing for the lag, scale errors are determined for speeds decreasing after attaining the highest speed of the range in the scale error test. At each test point the speed is brought down to but not below the desired value. The lag is the difference in the errors of the instrument at any one speed.

Friction.—Friction in the pivots and bearings of the instrument mechanism causes a lag in indication, which is considerably reduced if not entirely eliminated by vibration.

Since instruments installed on aircraft are ordinarily subjected to vibration, a small amount of friction in the mechanism of tachometers can be tolerated and is perhaps advantageous in damping out the indication of minor fluctuations. Excessive friction, however, results in a jerky motion of the pointer and often renders the instrument practically worthless.

The effect of the friction is determined by noting at the various test points the reading of the instrument before and after tapping. The difference is defined as the error due to friction.

Position errors.—Error arising from a change in orientation or position of an instrument are those resulting from lack of static balance of the mechanism. This is inherent in a centrifugal instrument since the sliding collar and the rotating weights are unbalanced and vary in their effect on the indication as the instrument is rotated. The effect is usually small.

Dynamic balance in the mechanisms of tachometers is desirable but not absolutely required except in the case of the centrifugal tachometer where a lack of dynamic balance of the governor element results in excessive vibration.

The effect of change in the orientation of tachometers, or the position error, is obtained by determining the difference in the errors of the instrument in two scale error tests, one with the instrument in the normal operating position and the other with the instrument in any other desired orientation. In the test specified by the Army and Navy Air Services the instrument is mounted so that, with the plane of the dial remaining vertical, the zero on the dial is 90° of arc from its position during normal operation (see fig. 25). This orientation is chosen because frequently due to interference between the flexible drive shaft and the other

a period of 3 hours while the instrument is operated at an indicated speed of 2,000 r.p.m. The apparatus with five instruments undergoing test is shown in figure 24. Further, the amplitude of oscillation of the pointer is noted in the frequency range 1,000 to 2,000 c.p.m. After being subjected to the vibration the instrument is given a scale error test the results of which are compared with those of a test previous to the vibration. The mechanical condition is determined by inspection for loosened screws or parts.

Overspeed.—In service the instrument may be momentarily subjected to a speed in excess of its range which should not affect the accuracy.

The overspeed test consists of subjecting the instrument for a period of 5 minutes to a speed 500 r.p.m. greater than the maximum indication on its dial. The maximum range of the commonly used instru-

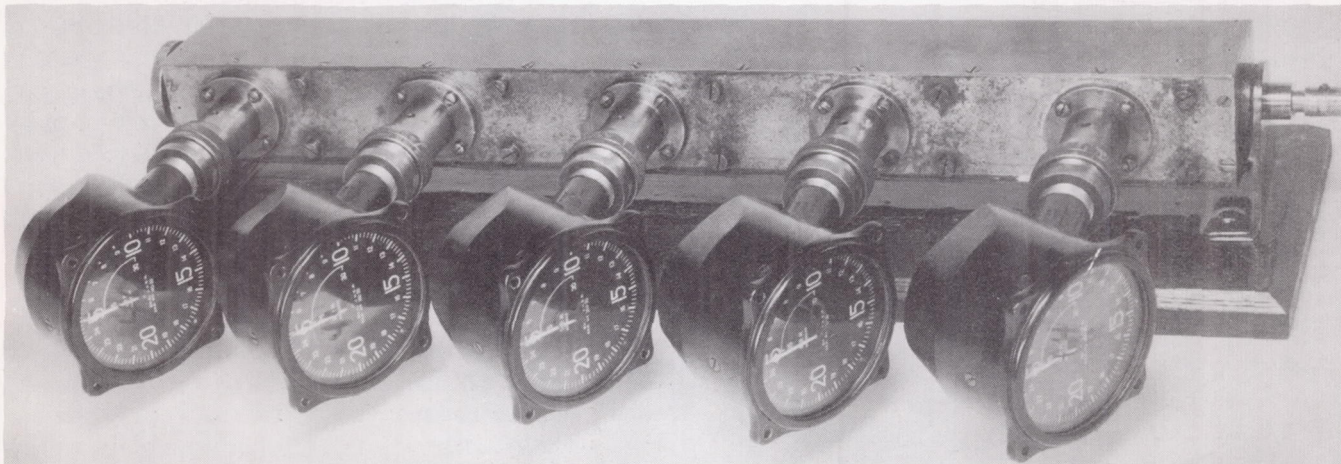


FIGURE 25.—Centrifugal tachometers undergoing test for position error. The instruments have been deflected 90° laterally with the dials remaining vertical.

equipment usually present behind the instrument panel it is necessary so to mount the tachometer.

Vibration.—Instruments must ordinarily withstand considerable vibration in service. This vibration has been measured by Zand by means of an instrument which photographically records the frequency and the amplitude of the vibration of the instrument board (reference 19). Its size is such that it can be installed on the instrument board in place of any of the $2\frac{3}{4}$ -inch standard dial size instruments. The results of tests show that in general the instrument board vibrates with a frequency equal to the speed of the engine and that the amplitude of vibration is by far the greatest in the fore and aft direction, with a magnitude depending upon the type of airplane and the number and location of the instruments on the panel.

Tachometers are tested for two effects—(a) the effect of vibration for a certain period of time on the scale errors and mechanical condition and (b) for excessive pointer oscillation. The instrument is subjected to the standard vibration at a frequency in the range 1,500 to 2,000 cycles per minute (c.p.m.) for

instruments is 3,000 r.p.m., so that the indicated test speed is 3,500 r.p.m. The effects of the overspeed are determined by a comparison of the scale errors obtained before and after the overspeed.

Temperature errors.—Changes in temperature produce a change in the physical dimensions of the parts of the mechanism and a change in the stiffness of the elastic elements. There may be difficulty in securing satisfactory operation at low temperatures if congealing of the lubricant occurs. Unless a differential effect is present, the first effect is of minor importance. The second effect requires compensation if extreme accuracy is required.

The standard temperature at which aircraft instruments are tested are $+45^\circ$ and -35° centigrade. At these two temperatures tachometers are subjected to scale error tests, the differences between the results of which is used as a measure of the effect.

For electrical tachometers additional temperature tests are frequently found desirable since the temperature effects are not necessarily proportional to the temperature. These consist of, first, varying the tem-

perature of the generator while that of the indicator is held constant at the desired value, and, second, varying the temperature of the indicator while that of the generator is held constant.

Seasoning and speed acceleration test.—Tachometers are subjected in service to rapid changes in speed which requires ruggedness in the instrument. Further, since the indication of most types of tachometers depends upon the deflection of an elastic element, the calibration may change due to imperfect seasoning. Seasoning may be defined as the process of relieving internal stresses in the elastic members to such a degree that no further relief takes place in service.

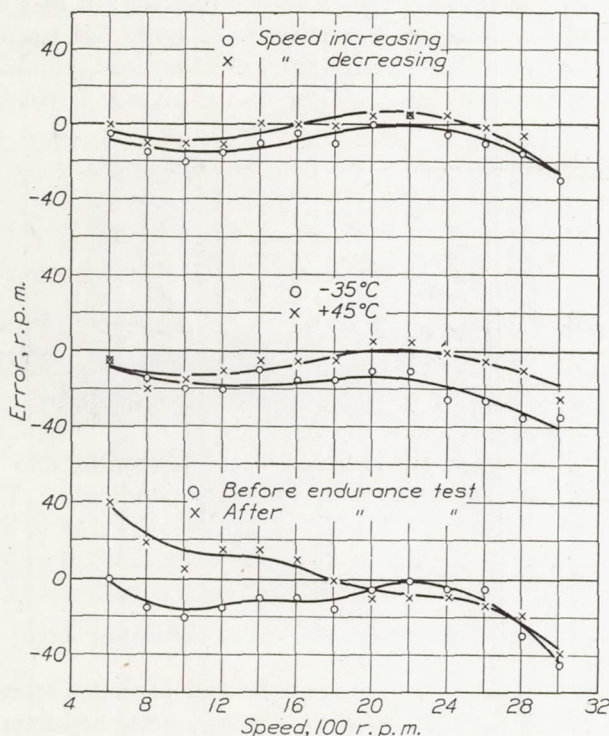


FIGURE 26.—Errors of a well-adjusted centrifugal tachometer. The curves show the scale errors, the lag, the effect of temperature, and the effect of a 300-hour endurance test.

The speed-acceleration test is a method of measuring the performance in both of these respects.

The test consists of the application of 500 successive accelerations by changing the indicated speed from 0 to 1,500 r.p.m. within a period of 1 second. In this test mechanical tachometers are connected to the motor through an 8-foot length of flexible shafting, in order to approximate more closely service conditions. The scale errors determined before and afterwards are compared in order to measure the effect.

Endurance.—Tachometers are likely to change their calibration or to fail entirely owing to the effects of wear in service. Their endurance characteristics are determined by operating them at an indicated speed of 2,000 r.p.m. for a period of 300 hours. Following this run, usually 1 hour after its completion, the instruments are given a scale error test, the results of which

are compared with a scale error test made just previously to the endurance run.

It should be noted that a change in calibration also occurs, due to another effect. If an elastic body is subjected to a change in load, which is then maintained constant, the deflection of the elastic body gradually increases with time. This increase is known as drift or creep. Drift in the spring, and thus in the indication, of centrifugal tachometers takes place during the endurance test. If desired to separate the drift from the effect of wear, the instrument should be calibrated immediately after and also about 24 hours or more after the endurance run. The difference in the errors in these two tests affords a measure of the effect of the drift, while the difference between the last test and the one just before the endurance run is a measure of the effect of wear.

Magnetic shielding.—In common with other electrical indicators, the indicator of electrical tachometers must in general be shielded magnetically in order to eliminate as far as possible the effect on the magnetic compass. The degree of this shielding is determined by noting the deflection of a standard type compass when the centers of the two instruments are 8 inches apart. The compass must be in a horizontal magnetic field 0.18 gauss in strength.

PERFORMANCE OF TACHOMETERS

The data on performance given in this section are for the best grade of instrument which is at the present time available commercially. It is of course obvious that selection is necessary in order to obtain an instrument of this performance, since an individual instrument of any given design may have, for one cause or another, an inferior performance.

A. CENTRIFUGAL TYPE

The scale errors of a well-adjusted instrument are shown in figure 26 by the points marked "Speed increasing." The tolerance in the current specifications of the air services is a scale error not to exceed 10 r.p.m. in the middle range of the indicated speeds and an error less than about 1 percent of the maximum indicated speed at other speeds.

The lag typical of a first-class instrument is shown in the two upper curves of figure 26. It does not exceed 10 r.p.m.

The position error, determined for the two positions given in the description of the test, usually has an average value of about 10 r.p.m. It varies considerably with speed, however, in one design of tachometer ordinarily varying from 5 to 20 r.p.m.

Under vibration the total deflection of the pointer with reference to the dial of a centrifugal instrument does not ordinarily exceed an amount equivalent to an indication of 20 r.p.m. (2.4° of arc). The average

change in error of an instrument before and after being subjected to the standard vibration at a frequency of about 1,500 c.p.m. for 3 hours is less than 10 r.p.m. for good quality instruments.

An overspeed of 500 r.p.m. on tachometers properly designed to meet this requirement causes substantially no average change in the errors. Usually a stop is provided so that the spring is prevented from deflecting beyond the amount obtained at an indicated speed slightly in excess of the rated range of the tachometer. In figure 4 such a stop is shown attached to the fixed upper sleeve.

The effect of changes in instrument temperature is shown in figure 26 for a good quality tachometer. Assuming that the effect is due to the change in the elastic modulus of the steel spring which balances the centrifugal force and that the deflection of this spring is proportional to the speed, the difference in the slopes of the best straight lines through the curves should be of the order of 2 percent (reference 14). Actually the temperature errors of centrifugal instruments are much smaller which is partly due to compensating changes in dimensions in the centrifugal element and to the lack of direct proportionality in the relation between speed and deflection of the spring. Thus in figure 21 the difference in the slopes, or the change in the scale value, of straight lines through the curves for $+45^{\circ}$ and -35° C. is about 1.2 percent. The instruments are ordinarily not compensated for temperature.

The average change in error before and after subjecting instruments 500 times to a change in indicated speed from 0 to 1,500 r.p.m. in 1 second is less than 10 r.p.m. for a representative instrument of high quality. Since the seasoning effect usually results in a stiffening of the elastic elements, the reading at a given speed is usually lower after the test.

The effect of an endurance run on a good quality instrument is shown in figure 26. The results of two scale error tests are given, one before the endurance run and one immediately afterwards. The difference between the two curves is a combined measure of the drift of the elastic element and wear in the mechanism. In tests made 24 hours after the completion of the endurance test, instruments of this type usually show a recovery from the drift effect to the extent of about 5 r.p.m. Ordinarily the results of the tests made just before and about 1 hour after the endurance run are compared. The average change in the errors in these two tests does not exceed 20 r.p.m. for good quality instruments.

B. CHRONOMETRIC TACHOMETERS

The scale errors of chronometric tachometers of the best quality can be reduced to an average value less than the inherent sensitivity of its mechanism which

may be defined as the speed range divided by the number of teeth in the ratchet gear. (See H in fig. 7.) This is of the order of 10 r.p.m. in most designs. Scale errors are those caused by improper adjustment of the escapement mechanism for the correct periodicity of vibration. When improperly adjusted, the scale errors are directly proportional to the speed.

Laboratory tests show that for properly designed instruments the average change in scale errors due to vibration, overspeed, angular acceleration, and seasoning are of the order of ± 5 r.p.m.; in other words, negligible. The lag is likewise small.

The percentage change in scale errors due to change in temperature from -35° to $+45^{\circ}$ C. does not exceed 0.5 percent if the instrument is designed to operate at temperatures as low as -35° C. An important cause of failure to operate is due to the use of a lubricant in the drum of the main spring which freezes at a temperature above -35° C. The use of a mixture of deflocculated graphite and oil with a pour point of -40° C. or lower has been found to be satisfactory.

Errors arising from a change in temperature are caused by insufficient or overcompensation of the escapement mechanism. The change in stiffness with temperature of the hairspring controlling the motion of the balance wheel is compensated by using a balance wheel with a bimetallic rim designed so as to expand with increase in the stiffness of the hairspring and to increase its moment of inertia correspondingly. The congealing of the lubricant of the balance staff of the escapement tends to decrease the amplitude of vibration of the balance wheel, causing it to vibrate at a higher frequency which results in a lower indication of a given speed.

Chronometric tachometers do not have a progressive change in their scale errors with continued operation. Wear of the mechanism due to continued operation or to repeatedly subjecting the instrument to rapid accelerations of speed is indicated by a slipping back of the pointer during the time interval in which the indication ordinarily remains constant. This, strictly speaking, is a failure to operate rather than an error in indication and is caused by wear between the teeth of the ratchet wheel (gear H, fig. 7) and its pawl. An instrument of the best grade should on the average withstand 500 hours of operation in service before requiring repair.

C. MAGNETIC TACHOMETERS

Data on the performance of very few magnetic tachometers designed for aircraft use are available. This type is very little used and rarely considered when accuracy is desired.

The errors of the instrument which are commonly small or are dependent only on care in adjustment are scale errors, lag, and overspeed. Temperature errors

and, in common designs, the effect of endurance running are both inherently large. Magnetic shielding of the instrument is necessary to avoid affecting the compass.

The temperature error is caused by the increase in electrical resistance of the indicating disk and the decrease in field strength of the permanent magnet as the temperature increases. The two effects are additive and introduce relatively large errors. The methods of compensation have been described in the section in which magnetic tachometers are described. The

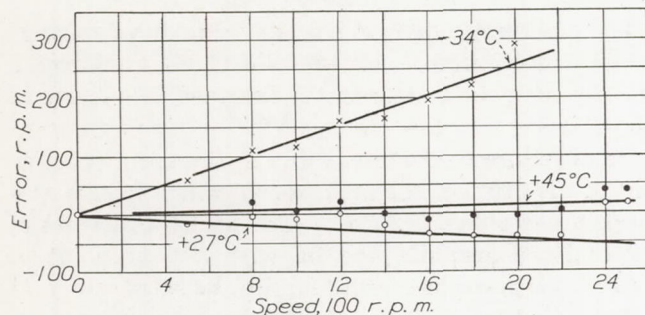


FIGURE 27.—Change in scale error with temperature of a magnetic tachometer.

effect of temperature on an instrument which has not been properly compensated is shown in figure 27.

Wear in the pivots or bearings of magnetic tachometers is, in the common designs, likely to affect the gap between the disk and magnet, a small change in which causes a large change in the calibration. Vibration greatly accelerates this process.

D. DIRECT CURRENT TACHOMETERS

The scale errors of a well-adjusted instrument will not exceed twice its least reading, which in an instrument with a pointer motion of 270° of arc is 10 r.p.m. The lag is of negligible amount. The position error of the indicator of instruments thus far tested does not exceed, on the average, twice the least reading.

Indicators which operate on a low-power input will not withstand the effect of airplane vibration and therefore must be mounted in a vibration-absorbing case. In designs in which the generator has a relatively large power output, the indicator is more rugged and in general will withstand a moderate amount of vibration. The vibration causes wear in the pivots of the indicator. It should be noted that the free frequency of the coil, spring and pointer combination is much lower than that of the vibration usually experienced. The case vibrates but the elastic system tends to remain fixed. The resulting relative motion is electromagnetically damped.

The temperature errors for an uncompensated instrument are shown in figure 28. The average change in the errors in the temperature range -35° to $+45^\circ$ C. of a compensated instrument should not exceed 20 r.p.m. and may be as low as 10 r.p.m. See the section

on "Characteristics of d.c. Tachometers" for discussion of the methods of compensation.

The effect of an endurance test on the best instruments causes an average decrease in the indication which will not exceed 20 r.p.m. The indicated speed is always decreased because in general the strength of the permanent magnets tends to decrease with time and the brush resistance to increase, due to the accumulation of dirt on the commutator of the generator.

The unshielded indicator will cause deflections upward of 10° on a magnetic compass in its vicinity. The addition of a soft-iron case around the indicator reduces this effect to a maximum of 4° when the two instruments are 8 inches from center to center.

E. ALTERNATING CURRENT TACHOMETERS

The performance of these instruments in tests for scale error, lag, position error and vibration is about the same as that of the d.c. type. There is also the same necessity for magnetic shielding.

(a) *Single-phase type.*—The errors due to change in instrument temperature are due to the effect on the field strength of the permanent magnets and on the resistance of the windings of the generator and of the indicator. There is also an effect on the output of the rectifier. Temperature compensation is essential.

The performance of the generator in an endurance test will be inherently better than that of a d.c. instrument, due to the absence of the commutator brushes.

No test data are available on these instruments.

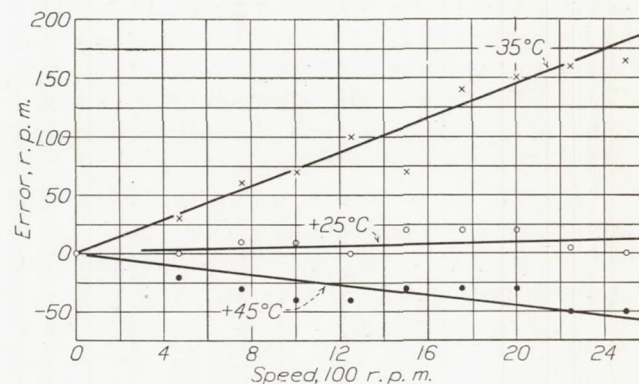


FIGURE 28.—Changes in scale error with temperature of a Horn electric tachometer.

(b) *Two-phase type.*—The output of the generator is affected by temperature changes for the causes stated above. Changes in temperature affect the indicator in a very complex manner. The satisfactory compensation of instruments of this type is a recent and outstanding development. The average change in the errors for the two conditions, one in which the generator is at -10° C. and the indicator at -35° C. and the other in which the generator is at $+60^\circ$ C. and the indicator at $+45^\circ$ C., does not exceed 20 r.p.m. for well compensated instruments. The compensation is as good at intermediate temperatures.

An endurance run of 300 hours on the generator of one model of this type of instrument shows that the resulting average change in reading is within 20 r.p.m.

In the larger number of instruments the effect of vibration is manifested by an excessive increase in reading over the central portion of the range in indication. The effect is probably due to wear in the pivots of the indicator. A more adequate measurement of the effect of wear in the pivots of the indicator is obtained in the speed-acceleration test. The effect on the small number of instruments tested was an average change in reading of approximately 10 r.p.m.

(c) *Three-phase type*.—No test data on this type of instrument are available.

F. SOLENOID OPERATED CHRONOMETRIC TACHOMETERS

In general this instrument is subject to the same errors as a chronometric tachometer. Special difficulty is experienced in obtaining satisfactory operation at low temperatures because of the additional power required to operate the chronometric mechanism owing to congealing of the lubricant. All of this power is obtained from the solenoid which, on account of limitations of space, is designed so as to require nearly full voltage during room temperature

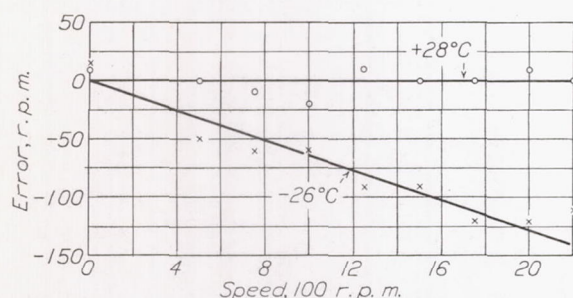


FIGURE 29.—Changes in scale error with temperature of solenoid-operated chronometric tachometer.

operation. The scale errors of an instrument at $+28^{\circ}\text{C}$. and -26°C . are shown in figure 29.

G. COMMUTATOR-CONDENSER TACHOMETERS

The errors of the commutator-condenser type tachometer may be conveniently divided into scale errors, temperature errors, and errors due to variation in voltage supplied.

The scale errors can be reduced to a value as low as the least reading of the indicator, since the scale divisions are approximately equally divided for speed.

Temperature errors are caused by the effect of temperature on the capacity of the condenser and on the performance of the indicator. The capacity of a well-designed mica condenser is affected by variations in temperature only by the change in the physical dimensions which is negligible. The indication of speed is independent of the resistance of the circuit

within the limits previously discussed, but depends upon the strength of the permanent magnet and the stiffness of the spring of the indicator, both of which are affected by temperature changes. If the indicator is compensated for the effect of temperature on its resistance and is also used to indicate the proper voltage, the effect of temperature on the voltage indication is the same as the effect on the speed indication. In this case the temperature error is compensated by a proportional change in the voltage.

The indications of the instrument are directly proportional to the voltage supplied, which can be maintained constant for long intervals of time by means of the automatic voltage regulator previously described.

H. ASKANIA PNEUMATIC TACHOMETER

The differential pressure developed by the pump unit is practically independent of the density of the air and of the temperature of the instrument. The pressure developed by the pump unit is pulsating and requires damping by means of a capillary tube in the line. In aircraft an indicator of the aneroid type would be used which would be subject to errors of the same type and amount as those of pitot-static airspeed indicators as described in reference 20.

ENGINE LOG INSTRUMENTS

In the flight testing of aircraft, in the operation of aircraft, and in special installations in connection with research problems, a record of the engine speed during flight and of the total number of hours of operation may be desired. In operating aircraft a record of the speed of the engine is useful in indicating any abuse to which the engine may have been subjected during flight and in determining its operating characteristics. A knowledge of the total number of hours of operation is of value in indicating when it is necessary to overhaul the engine. In order to coordinate the results of flight test data a record of the engine speed obtained automatically may be preferable to the recording of such information at frequent intervals by an observer.

There are three classes of engine log instruments which are in use, viz, the recording tachometer, the running-time meter, and the revolution counter, all of which are of the mechanical type. Both the recording tachometer and the running-time meter are driven from the engine by means of a flexible drive shaft. The revolution counter is usually designed to be attached to the engine by means of a two-way adapter directly at the connector provided for operating the tachometer drive shaft. In one make of recording tachometer the revolution counter is included as an integral part of the instrument.

RECORDING TACHOMETERS

The recording tachometer both indicates and records continuously the speed of the engine during the total operating period. The instrument consists of, first, a speed-measuring element and, second, a recording mechanism containing several rollers, one of which, the feed roll, rotates at constant speed. A strip of

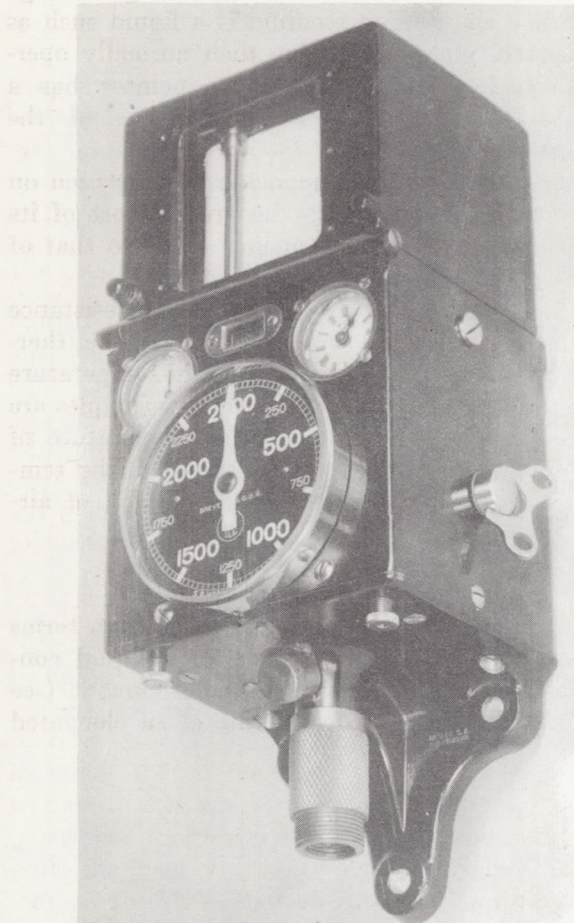


FIGURE 30.—Hasler "Tel" chronometric recording tachometer.

paper is fed from a magazine roll to the feed roll and thence to a receiving roll. A stylus actuated by the speed-measuring element bears lightly on the surface of the paper and traces a record of the speed. The abscissa and ordinate of this form of chart represent time and engine speed, respectively.

A record of the engine speed is sometimes made by photographing at intervals the face of a tachometer together with that of other instruments (references 31 and 41). An arrangement of this kind is known as a "dummy observer."

Hasler "Tel."—A photograph of the Hasler "Tel" recording tachometer is shown in figure 30. The instrument is of the chronometric type and is designed to record, first, a continuous trace of the engine speed; second, the time and duration of a flight; and, third, the trip revolutions of the engine. The surface of the recording paper is chemically prepared and is white in

color so that a practically black trace is described by a brass stylus. The recording rollers are designed for a capacity of 20 feet of paper, which length is sufficient for 30 hours of operation.

A spring-wound clock is provided as an integral part of the instrument. The weight complete is 10½ pounds and the dimensions 11½ by 4 by 3¼ inches. Its size is such as to preclude its mounting on the instrument panel in place of the tachometer already installed. (See references 37 and 39.)

B.S. recording tachometer.—A recording tachometer which may be installed on the instrument panel in place of the 3¼ inch round dial instrument has been constructed at the Bureau of Standards for the Bureau of Aeronautics of the Navy Department. It is a Van Sicklen chronometric tachometer modified to include a recording element. (See fig. 31.) The recording element is similar in general design to that of the Hasler "Tel" recording tachometer with the exception that it is built on the rear of the instrument so that it increases the dimension of the case in depth only. A commercial recording paper which is dark in color and is coated on one side with finely divided white wax particles is used with this instrument. As the paper is fed over the rolls a line of the wax particles is removed by the stylus, thus leaving a clearly defined trace.



FIGURE 31.—Bureau of Standards-Van Sicklen recording tachometer.

The trace becomes less well defined with decrease in temperature, becoming indefinable at about -20°C .

In order to facilitate the interpretation of the record, speed reference lines representing the even 100 r.p.m. speed intervals are automatically traced as the paper is fed through the recording mechanism. The weight of the instrument is approximately 3 pounds.

RUNNING TIME METER

This instrument registers the elapsed time during which the engine is in operation. The mechanism of the instrument is similar to that of a chronometric tachometer excepting that the speed-indicating mechanism of the latter instrument is replaced by a dial-type device for counting the beats of the escapement. Combinations of a chronometric tachometer and a

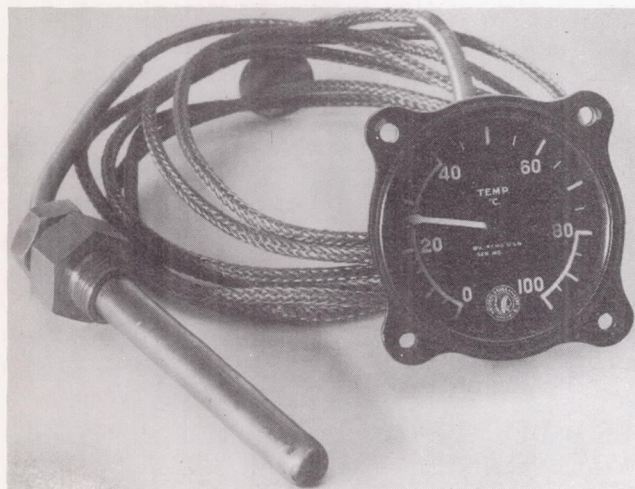


FIGURE 32.—Vapor-pressure type aircraft engine thermometer.

running-time meter are available, as in the Hasler Telmot Flight-O-Meter. The running-time meter may also be obtained as a complete instrument by itself, in which case it is usually driven by a flexible drive shaft connected with the tachometer drive shaft by means of a 2-way adapter.

ENGINE THERMOMETERS

USEFULNESS AND TYPES

Aircraft engines operate most efficiently when the temperatures of the lubricant and cylinders each remain within a limited range. Ordinarily the temperature of the lubricating oil of air-cooled engines and of the cooling liquid of liquid-cooled engines is measured. The practice is growing of measuring in addition the cylinder-head temperature of air-cooled engines. An indication of the temperature of the lubricant is of value when means for its control are provided, and similarly a knowledge of the temperature of the cooling liquid is essential in the control of manually operated radiator shutters. The temperature of the cylinders of air-cooled engines cannot normally be controlled, but is of primary interest as an indicator of trouble. One of the precautions always observed by a pilot before taking off is to ascertain that the temperature of the lubricant or cooling liquid has risen to and remains at the normal operating value.

Thermometers used in aircraft to indicate the temperature of various parts of the engine are of three types—(a) vapor pressure, (b) liquid expansion, and (c) electrical. All of the instruments are distant indicating.

The temperature of the cooling liquid of liquid-cooled engines and of the lubricating oil has been measured

almost exclusively for a number of years by vapor-pressure instruments. They are standardized with regard to the sizes of the cases and dials (1½ inches in diameter) and are used in either of the two ranges, 0° to 100° C. (32° to 212° F.) or 30° to 200° C. (86° to 392° F.). The lower range instrument is used in measuring the temperature of the oil or of the cooling water. The thermometer having the higher range is used when the cooling medium is a liquid such as ethylene-glycol, since the engine then normally operates at a higher temperature. The pointer has a motion of 300° of arc for both ranges of the instrument.

The liquid expansion thermometer is little used on aircraft, owing principally to the greater cost of its manufacture to have a performance equal to that of the vapor-pressure type.

The electrical instruments include the resistance and the thermocouple types. The resistance thermometer has been designed to measure the temperature of either the cooling water or oil. Thermocouples are particularly useful in measuring the temperature of metal parts of the engine, as, for example, the temperature at some point of the cylinder wall of air-cooled engines.

A. VAPOR-PRESSURE THERMOMETERS

The vapor-pressure thermometer indicates in terms of temperature the vapor pressure of a liquid contained within the instrument. The instrument (see fig. 32) is a closed system consisting of an elongated

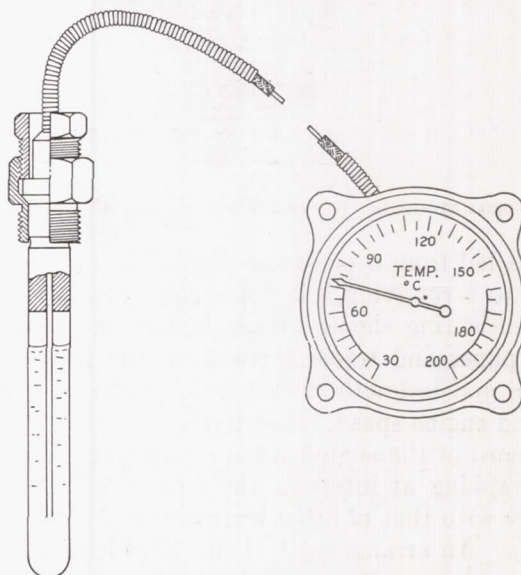


FIGURE 33.—Diagram of vapor-pressure thermometer.

bulb, a capillary tube, and a pressure gage, and is partially filled with a liquid having a vapor pressure conveniently measurable in the desired temperature range. The bulb is installed on the engine at a point where a knowledge of the temperature is desired. The capillary tube connects the bulb with the indicator mounted on the instrument panel.

A diagram of the vapor-pressure thermometer is shown in figure 33. The pressure element within the

indicator is a Bourdon tube, the internal volume of which is relatively small. The end of the capillary tube extends into the liquid in the bulb so that the Bourdon tube fills with liquid by flowing, and not by condensing, when the temperature of the bulb is changing from a condition where it is colder than the indicator to one where it is hotter. By this arrangement the time lag of the thermometer at the transition point is greatly reduced.

The temperature of the free surface of the constrained liquid is indicated, and thus in order that the temperature at the desired point be indicated it is necessary that the design be such that the free surface of the liquid is always within the bulb. In order to obtain this under the normal conditions of operation, during which the bulb is at a temperature higher than that of the indicator, the volume of the bulb is made larger than that of the combined volumes of the capillary and Bourdon tubes. In this case the liquid completely fills the Bourdon and capillary tubes, and partially fills the bulb.

The vapor pressures of liquids do not vary uniformly with temperature, but a scale approximately evenly divided is obtained in instruments by means of a suitably designed multiplying mechanism. The development of an instrument with an equally divided scale has been a big factor in its adoption for general use on aircraft. Table I gives the vapor pressure and the rate of change of vapor pressure with temperature for the commonly used liquids. The wide variation in the rate of change of vapor pressure for the various liquids is a measure of the difficulty in obtaining an equally divided temperature scale.

TABLE I

[Vapor pressure and rate of change of vapor pressure at various temperatures]

Liquid	Vapor pressure in atmospheres				Rate of change in atmospheres per ° C.			
	Temperature ° C.							
	0	50	100	193.8	0	50	100	190
Sulphur dioxide (SO ₂).....	1.53	8.18	28.8	-----	0.073	-----	0.55	-----
Methyl ether (C ₂ H ₆ O).....	2.54	11.25	32.6	-----	.10	-----	.57	-----
Methyl chloride (CH ₃ Cl).....	2.50	10.7	31.4	-----	.10	-----	.55	-----
Ether (C ₄ H ₁₀ O).....	.24	1.68	6.39	35.5	-----	0.053	.29	0.51

Installation precautions.—The vapor-pressure thermometer should be installed so as to avoid breakage of the capillary tube due to excessive vibration, chafing, or straining where it joins with the bulb. Breakage at the bulb due to vibration can be greatly reduced by taping the tube, just above the reinforcement, to the part vibrating with the engine. This appears to distribute the deflection of the tubing over a short length. Local overheating at any point along the tube may produce large errors in the indications of the instrument. Wherever possible the excess

length of tubing should be coiled and securely fastened to a structural member of the aircraft at a point which is comparatively free from vibration.

B. LIQUID-FILLED THERMOMETERS

The liquid filled thermometer is actuated by the thermal expansion of a liquid contained within the instrument and has essentially the same parts as the vapor-pressure thermometer. The increase in volume of the contained liquid (usually alcohol or ethyl ether, or in some instances mercury) with increase in temperature is linear for all practical purposes within the range of temperature from 0° to 100° C. The scale is therefore divided evenly and equally positive indications are obtained at either end of the scale. Usually the instrument is filled so that the contained liquid is at a considerable pressure (100 pounds per square inch) when its temperature is 0° C. This is necessary so that the Bourdon tube will remain under tension while the liquid in it and in the capillary contracts as the temperature is lowered to -35° C. At 100° C. the internal pressure may amount to 700 or 800 pounds per square inch depending upon the thermal coefficient of expansion of the liquid used and the stiffness of the Bourdon tube.

The indications of instruments are affected considerably by variations in the temperature of the liquid in the Bourdon and capillary tube. The effect of change in temperature of the Bourdon tube is readily eliminated by means of a bimetallic strip, properly inserted in the indicator. Considerable difficulty is experienced in compensating at reasonable cost for the effect of temperature changes in the capillary tube. The simplest method depends upon the use of capillary tubing having a bore so small that a change in the volume of the liquid contained within it produces an inconsequential error in indication.

C. ELECTRIC THERMOMETERS

General electric resistance thermometer.—An electrical resistance thermometer for use in measuring the temperature of the engine oil or cooling liquid has been developed recently (reference 18). The instrument consists of a temperature sensitive resistance **A**, figure 34, in series with one of the coils of part **C**, and a fixed resistance **B** in series with the other coil of part **C** of the indicator. A 12-volt source of electrical current is connected in series with each resistance. Part is in the field of a permanent magnet and is free to rotate to a position of equilibrium under the action of the opposing torques of a hairspring and of the interaction of the magnetic fields of the differential currents in the coils and the magnet. The indication is independent of the voltage within wide limits. Resistance element is mounted within a sealed cartridge which is installed

on the engine at the point at which the temperature is required. The case of the indicator floats on sponge rubber within an outer case the dimensions of which conform to the standard for the 1½-inch dial size. The indicator mechanism is magnetically shielded. The pointer has a motion of 90° of arc for the temperature range.

This instrument is adaptable for use in measuring free-air temperature, in which case the cartridge is ven-

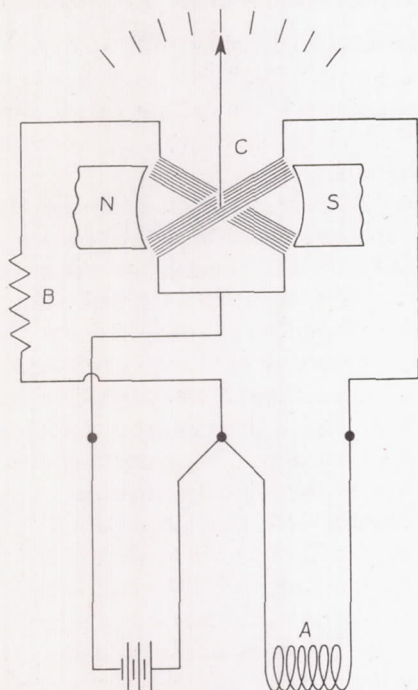


FIGURE 34.—Electric circuit of G.E. resistance thermometer.

tilated and is mounted on a strut in a position removed from the blast of the hot exhaust gases of the engine.

Thermocouple thermometers.—When one junction point of a loop composed of two dissimilar metals such as copper and constantan is at a temperature differing from that of the other junction point, an electrical current will flow through the circuit. The magnitude of the current depends upon the difference in the temperatures of the two junction points. In thermocouple thermometers for aircraft a suitable millivoltmeter calibrated in units of temperature is used as the indicator. One of the junctions, the cold junction, is installed within the case of the indicator and the other, the hot junction, is constructed in the form of a spark-plug gasket, or attached to an expanding rivet which is forced into a hole in the engine cylinder at the point at which the temperature is desired. In order to obtain indications of the actual temperature of the hot junction, rather than the difference in the temperature between the two junction points, a compensation is usually provided for the effect of variation in the temperature of the cold junction. When this compensator is within the indicator, as is usually the case, compensation is also

obtained automatically for most of the effect of changes in the temperature of the indicator.

The instruments available differ mainly in the method of compensation. One of these methods is illustrated by the Brown thermometer, a diagram of the indicator of which is shown in figure 35. The compensation is obtained with a bimetallic strip *B*, one end of which is mounted directly on a pole piece at *A* and the other end of which is fastened at *C* to the outer coil of one of the hairsprings attached to the pointer shaft. If the bimetallic strip is of proper design, any tendency of the pointer to deflect due to a change in the temperature of the indicator and cold junction is very nearly balanced.

The indicator of the Weston aircraft engine thermometer contains the bimetallic type of compensation. Its internal resistance is 13.5 ohms, part of which is swamping resistance for temperature compensation. Copper-constantan thermocouples are used. The pointer has a motion of 120° of arc for the range from 0° to 600° F. (−18° to 317° C.) or 0° to 350° C. The case is the standard 2¼-inch dial size. The leads of various lengths, including the engine thermocouple, have in all cases the same resistance of 2 ohms and are of stranded wire. The instrument is unique in the use of cover glasses of nonshatterable glass.

In the General Electric thermocouple thermometer (reference 54) a magnetic shunt, the permeability of which decreases with increase in temperature, is added to the magnet of the indicator. This controls the magnetic flux through the moving coils so as to

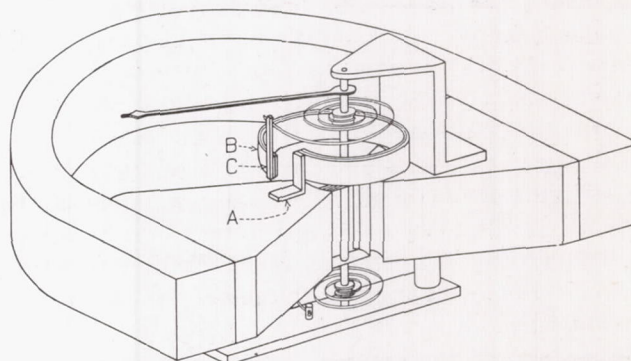


FIGURE 35.—Electric indicator showing the Brown cold junction compensator for thermocouple thermometers. *B* is the bimetallic strip, one end of which is fastened to the pole piece at *A* and the other to the hairspring at *C*.

compensate for the effect of change in the temperature of the cold junction and of the indicator, insofar as possible. Iron-constantan thermocouples are used.

In one type of thermocouple thermometer nine hot junctions are provided which may be installed in various locations on the engine. A selector switch and an indicator containing one cold junction are included with each instrument. With this equipment an indication of the temperature at any one of nine points on the engine may be conveniently obtained.

APPARATUS FOR TESTING ENGINE THERMOMETERS

Apparatus for scale-error tests.—The scale errors of an engine thermometer are determined in the laboratory by comparing its readings at a number of points within its range with those of a calibrated thermometer of the mercury-in-glass type or with those of a calibrated thermocouple. The testing apparatus consists of an insulated liquid bath in which are immersed the standard thermometer, the temperature sensitive elements of the instruments under test, and a stirrer driven by a small motor. The temperature of the bath is reduced by adding cracked ice or raised by means of an electric immersion heater.

Water is the most suitable liquid in calibrating instruments of the range 0° to 100° C. A cylinder oil with a pour point slightly below 0° C. which gives off relatively little vapor at 200° C., has been found particularly serviceable for testing instruments in the

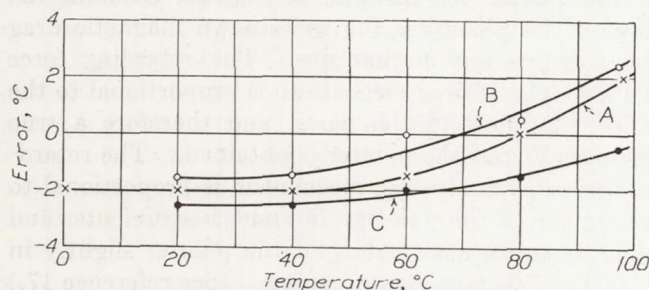


FIGURE 36.—Errors of a vapor pressure thermometer of good quality. Curve *a* was obtained with the gage and capillary at $+26^{\circ}$ C, *b* at $+45^{\circ}$ C, and *c* at -35° C.

range from $+30^{\circ}$ to 200° C. Tempering lavite, a compound of salts commercially available for tempering metals, can be used in the range above 125° C., and down to 30° C. when dissolved in water. The excessive length of time necessary to evaporate the water at about 125° C. makes it impractical to use the water-lavite solution.

For tests at airports and other field stations similar liquid baths are required. The test points can all be at or above the ambient temperature, so that a means for raising the temperature is all that is required. Calibrated mercury-in-glass thermometers are used as a standard.

Vibration and temperature control apparatus.—Engine thermometers are tested for the effects of vibration by mounting them on the apparatus described in the section on "Laboratory Testing of Tachometers Apparatus" and subjecting them to the standard vibration. Temperature chambers suitable for controlling the temperature of the indicators are also described in the section just referred to.

Pressure-control apparatus.—Vapor-pressure thermometers, and to a smaller extent liquid filled thermometers, are subject to errors resulting from extraneous deflections of the Bourdon tube of the indicator due to variations in the air pressure. An apparatus

consisting of a chamber capable of withstanding a partial vacuum and large enough to receive the entire calibrating apparatus described above is used in determining these errors. The pressure within the chamber is reduced by means of a vacuum pump. A mercurial barometer connected with the chamber indicates the absolute pressure.

PERFORMANCE OF ENGINE THERMOMETERS

A. VAPOR-PRESSURE THERMOMETERS

The tests described below for vapor-pressure thermometers are substantially those required for acceptance in the purchase specifications issued jointly by the Army Air Corps and the Bureau of Aeronautics of the Navy Department.

The same tests are made on both the 100° C. and the 200° C. instruments except for obvious differences due to the difference in the ranges. The performance of the two types is essentially the same if expressed in terms of pointer motion in degrees of arc; in terms of temperature the errors of the 200° C. instrument are from $1\frac{1}{2}$ to 2 times those of the 100° C. instrument.

Scale errors.—Each thermometer is subjected to the scale error test in order to determine that it is in operating condition and to evaluate the error at any desired number of points over the range of indication. The test is made by comparing the reading of the thermometer with that of a standard instrument when the bulbs of both instruments are immersed in a liquid bath the temperature of which is under control. During the test the capillary tube and the indicator are maintained at room temperature.

The scale errors of a well-adjusted thermometer with a range of 100° C. are shown in curve (A) of figure 36. The indication of the instrument is not as reliable at temperatures below, as it is above, 20° C. owing to relatively small rate of change of vapor pressure with temperature in this range and the consequent greater effect of friction in the mechanism.

Excess temperature.—Engine thermometers which are graduated in the range 0 to 100° C. are likely to be subjected in service to temperatures exceeding the range in indication. Within limits the accuracy in indication should not be affected by this treatment. The excess temperature test is made by comparing the readings of the instrument corresponding to a bulb temperature of 100° C. obtained before and after a 10-minute period during which the temperature of the bulb has been raised to approximately 110° C. The change in reading should not exceed 3° C. No data on the effect of excess temperature on the 200° C. instrument are available.

Drift.—Drift is manifested in a thermometer of the liquid-filled or vapor-pressure type by a gradual increase in indication after the temperature of the bulb has been raised to, and while it is being maintained

at, a value higher than that at which it was previously subjected. The drift test is made by subjecting the bulb of an instrument to approximately the maximum temperature of the range for a period of 1 hour. The increase in indication obtained during this time is a measure of the drift.

In good quality instruments of either range the drift does not exceed 2° C.

Temperature errors.—The errors caused by a variation in the temperature of the capillary tube and indicator are determined by repeating the scale error test with the temperature of the capillary tube and indicator, first at plus 45° C. and then at minus 35° C. The difference between the scale errors as obtained in these tests is a measure of the temperature effect.

Failure to function at the low temperature is in general due to insufficient liquid in the bulb or perhaps to freezing of an impurity in the liquid. These conditions are detected by a failure of the instrument to change its indication as the bulb temperature is varied. Insufficient filling may often be definitely demonstrated by the fact that progressively greater lengths of the capillary tubing must be immersed in the temperature bath as its temperature is increased in order to secure the indication of the bath temperature. In order to detect freezing of an impurity it is the practice in the low temperature test to reduce the temperature of the entire instrument to -20° C., so that it may freeze solid in the tubing undisturbed by the flow caused by differential temperatures in the parts of the instrument.

The temperature errors of a representative 100° C. instrument are shown in figure 36 in which curve (B) shows the errors with the gage and capillary tubing held at +45° C. and curve (C) with their temperature held at -35° C. The temperature effect is usually obtained by averaging the differences in the error at each test point, irrespective of algebraic sign. This average difference for curves (B) and (C) is 1.8° C. and should not exceed 3° C. for instruments of either range.

Vibration.—In the vibration test the indicator alone is subjected to the standard vibration for a period of 3 hours. It is also subjected to vibrations varying in frequency from 1,000 to 2,000 c.p.m. and the amplitude of the pointer vibration relative to the dial observed. During the latter test the thermometer bulb is maintained at a specified temperature within the usual range of temperatures to be measured on aircraft. The amplitude of the pointer vibration should not be such as to indicate a free period of the mechanism in the above range of frequencies nor should the functioning or performance of the instrument be affected. The latter requirements are determined by an examination of the instrument for loose parts and a comparison of the difference in the scale errors usually at 100° C. or 200° C. of the instrument obtained before and after the vibration.

The oscillation of the pointer during vibration is usually within 2° C. for 100° C. instruments and 3° C. for the 200° C. type.

If the natural frequency of vibration of the mechanism of an instrument coincides with that to which it is subjected, an excessive amplitude of vibration of the pointer may occur. The natural frequency may be shifted outside of the frequency range of vibration by redesigning the mechanism, which means in effect a change in the stiffness of the elastic element, or by addition of an inertia disk or a damping device. The inertia disk in the form of a flywheel is attached to the pointer shaft and in effect constitutes an inertial force opposing that of the vibrating elastic element, reducing both the natural frequency and amplitude of vibration. The use of the inertia disk does not interfere with the pointer assuming the true mean position of indication.

Chief among the damping devices for reducing the effect of vibration are the well-known magnetic drag and the air-drag mechanisms. The retarding force of the magnetic drag mechanism is proportional to the relative velocity of the parts, and therefore a true mean reading of the pointer is obtained. The retarding force of the air-drag mechanism is proportional to the square of the velocity in some instruments, and tends to produce a reading of the pointer slightly in error from the true mean reading. (See reference 17.)

Capillary temperature.—The capillary tube of an engine thermometer is likely to be subjected in service to localized heating, a condition which usually occurs when a portion of the capillary is attached to a frame member which is too close to the oil line or exhaust pipe. The effect of local heating ordinarily experienced is negligible in properly designed vapor pressure thermometers but not in liquid filled instruments. A capillary temperature test is made by subjecting a short length of the capillary tubing to a temperature of 100° C. while the indicator, bulb, and remainder of the tubing is maintained at room temperature. The change in indication obtained indicates the capillary temperature effect.

Reduced pressure.—The actuating elements of the indicators of both the vapor pressure and liquid filled thermometers are subjected externally to the pressure of the surrounding atmosphere. The indications of the instruments are affected as a consequence by variations in the altitude by an amount equal to

$$\frac{(P_o - P)}{R}$$

where $P_o - P$ is the change in atmospheric pressure and R is the rate of change of the vapor pressure with temperature at the temperature of the bulb. It follows that the effect depends upon the choice of the filling liquid and that it varies with the temperature of the bulb, decreasing as its temperature increases.

A test at reduced pressure is made by subjecting the entire instrument to an absolute pressure of approximately 12 inches of mercury. With the indicator and capillary maintained at room temperature ($+20^{\circ}\text{C.}$), the temperature of the bulb is then raised to 60°C. , or about 150°C. for instruments having a range extending up to 200°C. The reading of the instrument at this temperature and at the reduced pressure is compared with that at room pressure and the same temperature in order to obtain the effect of the reduced pressure. In instruments now available the effect is less than 3°C. for 100°C. instruments and 4°C. for 200°C. instruments.

Capillary strain.—The mechanical strength of the capillary tubing is determined by means of the capillary bending and strain tests. The bending test is made by flexing the capillary 20 times at one point through an angle of 90° around a cylindrical core of $\frac{1}{2}$ -inch radius. The strain test is made by clamping the capillary at a point approximately 6 inches from the indicator and suspending a weight of 25 pounds from the free end of the tubing for a period of 1 minute. This test is also made with the capillary clamped at a point approximately 6 inches from the bulb. Possible failure of the tubing is indicated by a large difference between the readings at a given bulb temperature taken before and after the tests.

B. LIQUID-FILLED TYPE

Except for the effect of reduced pressure and capillary temperature, the performance of liquid-filled instruments does not differ essentially from the vapor-pressure type (reference 5). The effect of reduced pressure is ordinarily negligible. As has been stated the effect of local changes in the temperature of the capillary tubing is excessive in the ordinary instrument.

C. ELECTRICAL THERMOMETERS

Electrical thermometers are tested for scale errors, temperature errors, and vibration in essentially the same manner as described for vapor-pressure thermometers. The indicator is tested for the degree to which it affects the magnetic compass exactly as described in the section on the methods of testing tachometers. In addition if the instrument requires a voltage supply, tests are made for the effect of its variation.

The time lag (reference 15) in indication of aircraft-engine thermometers is in general not a factor under the conditions of their use.

Resistance thermometer.—The instrument should be tested (a) for scale errors, (b) drift, (c) for the effect of changes in temperature of the indicator, (d) vibration, and (e) magnetic shielding. No laboratory data have been obtained at the Bureau of Standards. The performance should be substantially equal to that of

vapor-pressure thermometers if any advantage from its use is to be realized.

Thermocouple thermometers.—These instruments are at present made with a deflection of the tip of the pointer of approximately $2\frac{1}{2}$ inches for a range of temperature of 350°C. , which means the temperature can be read at best not closer than 1°C. and in flight under average conditions not closer than about 3°C. Tests show that the scale errors of instruments can be reasonably expected not to exceed 7°C. at any point on the scale.

Laboratory tests show that electrical indicators of the sensitivity used in the thermocouple thermometers do not ordinarily withstand vibration in that the calibration slowly changes, due to wear of the pivots.

The change in indication with change in temperature of the indicator is far larger than expected in the few instruments thus far tested, amounting to about one half of the change in temperature of the indicator. The results are probably not typical of well-adjusted instruments. It is believed that instruments now available will have errors not exceeding 17.5°C. when the temperature of the indicator varies from -25° to 45°C.

An additional error in service use, not determined by the laboratory tests, is the effect of the uncertainty in the temperature, and thus the resistance, of the copper or iron connecting wires. This effect is probably negligible in most instruments now available, in view of the relatively high resistance of the other parts of the circuit.

The indicator, as in the case of electrical tachometers, must be magnetically shielded. As a practical minimum the effect on a compass should not exceed 4° when 8 inches distant from its center.

PRESSURE GAGES

Aircraft engines are equipped with pumps for circulating the lubricating oil under pressure to the bearings. A pressure gage which indicates the pressure developed by the oil pump is used to determine its satisfactory operation.

In addition to oil pumps most aircraft engines are provided with fuel pumps for delivering the fuel to the carburetor. Information on the operation of the pump is obtained by measurement of the pressure developed.

Pressure gages may be conveniently grouped into two general classes—mechanical and electrical.

MECHANICAL PRESSURE GAGES

General design characteristics.—A diagram of a typical mechanical pressure gage is shown in figure 37. A Bourdon tube B is used as the pressure-sensitive element. It is of interest that the Bourdon tube is reported to have originated with Schinz in Germany in 1845. (See reference 48.) It is formed by

bending into the arc of a circle a length of thin walled metallic tubing which has been previously shaped to have in section the contour of an ellipse. One end of the tube is mounted on the base of the instrument so as to communicate with a threaded fitting. The other end is sealed off and connects with the multiplying mechanism through a suitable linkage. An increase in the pressure within the tube is accompanied by an increase in the cross-sectional area which gives

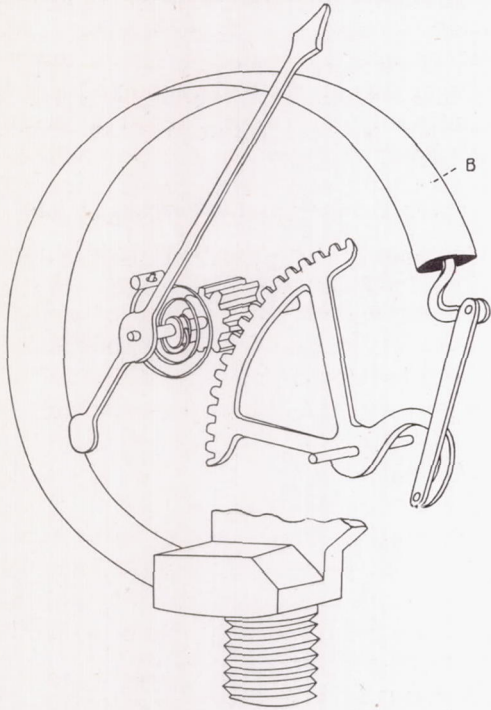


FIGURE 37.—Diagram of pressure gage of the Bourdon tube type.

rise to a force tending to straighten the tube and consequently to a displacement of the free end.

A deflection formula derived by Lorenz (reference 51) is stated by Rolnick (reference 59) to be reasonably accurate for tubes with a small ratio of thickness to width of cross section, and is given below.

$$\frac{A}{A_0} = \frac{1.16PR_0^2}{hbE}$$

Here A is the angular rotation of the Bourdon tube produced by the differential pressure P ; A_0 , the angular length of the tube; R_0 , the radius of the tube; h , the wall thickness; b , the thickness of the tube from center to center of the walls; and E , the modulus of elasticity.

For additional theory and data on Bourdon tubes see references 46 to 52, inclusive, and 58.

The multiplying mechanism of the gage consists of a link, a sector, and a pinion arranged as shown in figure 37. For convenience in calibrating, the point of connection of the link to the sector is made adjustable.

The gage is usually mounted on the instrument panel and is connected to the pump by means of copper tubing. The connection to the indicator and to the

point at which the pressure is measured is made by a fitting, such as is shown in figure 18 of reference 33.

Oil-pressure gage.—Oil-pressure gages are graduated in either of the two ranges, 0 to 120 and 0 to 200 pounds per square inch. As stated in the "Introduction" the diameter of the dials of oil-pressure gages is now fixed at 1½ inches and the spacing between the mounting holes is standardized, so that instruments of the various manufacturers may be interchanged. The weight of the instrument is approximately 6 ounces.

The design of the Bourdon tube depends upon the range of indication. In one instrument having a range of 0 to 120 pounds per square inch the tube is of hard-drawn brass and has an outside diameter of 1¼ inches, an elliptical section of ½ by ¾ inch, and a wall thickness of 0.011 inch.

Fuel-pressure gage.—The general appearance and the construction of the fuel-pressure gage are similar to those of the oil-pressure gage. The Bourdon tube, however, is constructed of much thinner metal, so that its stiffness is approximately one tenth that of the oil-pressure gage. The fuel-pressure gage is usually graduated in the range 0 to 10 pounds per square inch and weighs approximately 5 ounces.

Diaphragm type relay.—In order to conserve the supply of lubricant in case of breakage of the copper

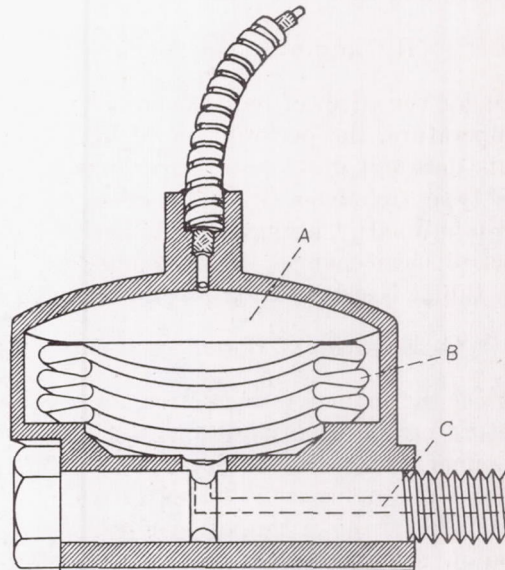


FIGURE 38.—Diagram of diaphragm relay for oil-pressure gages. The metal bellows B intervenes between the lubricating oil and the liquid in A which transmits the pressure to the gage.

tube connecting the oil-pressure gage with the engine and to decrease the lag in indication at low temperatures due to congealing of the oil within the connecting tube, pressure relay devices have been developed both here and abroad (references 16 and 17). A cross-sectional diagram of the essential features of such a device is shown in figure 38. The relay is mounted on the engine at the oil-line fitting and contains a diaphragm or metal bellows B. The space A outside of

the diaphragm, the connecting tubing, and the Bourdon tube in the indicator are completely filled with a liquid which has a low freezing point, a low viscosity, and a relatively low thermal coefficient of expansion. Mineral spirits (varnolene) has been found satisfactory. The pressure of the lubricating oil which connects to

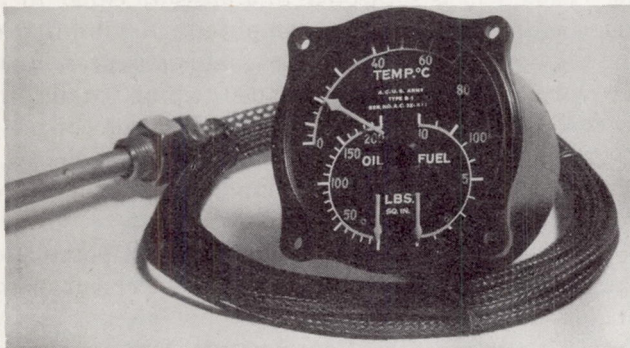


FIGURE 39.—Engine gage unit.

the inside of the diaphragm through hole *C* is transmitted through the diaphragm to the liquid and thence to the pressure gage.

Engine gage unit.—The oil and fuel pressure gage and the oil or cooling liquid thermometer are sometimes installed within a single case. The combination is known as the engine gage unit. The latest form is

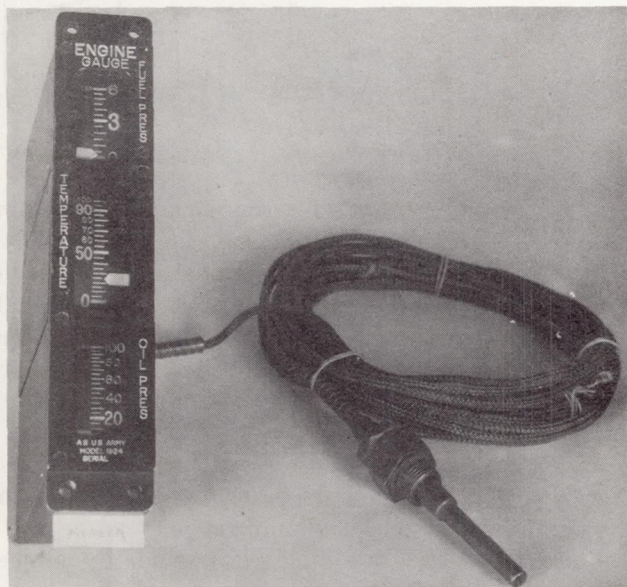


FIGURE 40.—Engine gage unit with approximately linear scale.

shown in figure 39, and an older form, in which the individual instruments are arranged vertically in tandem within a case, is shown in figure 40.

The instrument shown in figure 39 is mounted in a case which conforms to the standard 2 $\frac{3}{4}$ -inch dial size. Contrary to general practice the pointer of the fuel pressure gages moves counter-clockwise with increase in pressure. Its weight with a 22-foot capillary tube averages 1.9 pounds.

ELECTRICAL PRESSURE GAGES

The electrical circuit of the G.E. electrical oil or fuel pressure gage is the same as that of the thermometer shown in figure 34. The resistance *A* is made to vary with pressure by means of the deflection of a metal bellows the combination of which is mounted in a cartridge type container suitable for installation on the engine at either the oil- or fuel-line fitting. The indicator is of the same type as that used with the thermometer and similarly is magnetically shielded and is protected from the effects of shocks and vibration. The instrument operates on 12 volts and is stated to draw normally 50 milliamperes of current. The combined weight of the pressure element and indicator is 12 ounces.

APPARATUS FOR TESTING PRESSURE GAGES

The scale errors of oil-pressure gages are determined by means of a deadweight gage tester. The tester

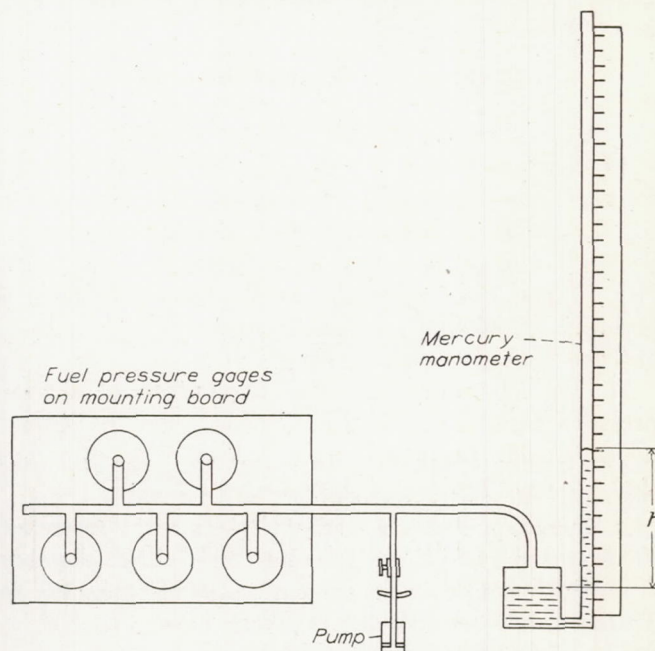


FIGURE 41.—Diagram of apparatus for testing fuel-pressure gages.

consists essentially of a vertical cylinder, a closely fitting piston provided with a pan for weights and a pump. The instrument to be tested is connected to the cylinder by means of suitable fittings and a connecting tube. The cylinder is filled with a light mineral oil. To obtain a desired pressure, a weight equal to the product of this pressure by the area of the cylinder is placed on the pan of the piston and the pump operated until the piston is supported by hydrostatic pressure. The effect of friction between the weighted piston and the wall of its cylinder is usually eliminated by spinning the piston before reading the instrument.

It has been found possible to operate the deadweight gage tester with a mineral oil with a pour point of

-40° C. This has made it possible to test oil-pressure gages at -35° C. without danger of the oil freezing in the tubing connecting the gage to the tester.

The arrangement of apparatus used in determining the scale errors of fuel-pressure gages is shown in figure 41. A mercurial manometer is used as the standard, which may be of the reservoir type as shown or of the U-tube type. In either case it should be noted that the pressure is determined by the difference in height. The required pressures are obtained by means of a hand pump.

Apparatus for controlling the temperature of the instruments during test and for subjecting them to vibration are described in the section, Testing of Tachometers.

For determining scale errors of both fuel and oil pressure gages at instrument repair stations a dead-weight gage tester designed for both ranges is most convenient. It is also feasible to use a calibrated gage as the standard, in which case a suitable pump is required.

PERFORMANCE OF PRESSURE GAGES

A. MECHANICAL TYPE

Mechanical pressure gages are subjected to tests for (a) scale errors, (b) friction, (c) vibration effect, (d) seasoning, (e) drift, (f) effect of suction and over-pressure, and (g) the effect of temperature.

A general discussion of most of the above tests is given in the section on Tachometers under "Methods of Test."

It should be noted that the construction of aircraft pressure gages to the accuracy needed offers in general no particular problem. This follows from the fact that the least reading of these gages is about 1 percent of the maximum range, for example 0.1 pound per square inch in the gage with a range from 0 to 10 pounds per square inch, and that an accuracy of at least 1 percent in most respects is usual in pressure gages used in engineering work.

Scale errors.—The scale errors of the pressure gage are determined by subjecting the instrument at the pressure connection to a number of specified pressures over its range and obtaining the corresponding instrument readings. The error is $R-S$, where R is the reading of the gage and S is the true pressure.

The scale errors of both fuel and oil pressure gages of good quality do not exceed 2 percent of the maximum range. Those of a typical oil pressure gage of good quality are given in curve A, figure 42.

Friction.—The effect of friction is found by subjecting the instrument to a given pressure and comparing the readings of the instrument before and after it has been tapped. The difference in the two readings indicates the effect of friction. The friction is usually obtained at a number of pressures over the range of

the instrument and amounts on the average to about 1 percent of the maximum range.

Vibration.—The effects of vibration are determined by subjecting the instrument to the standard vibration with a frequency between 1,500 and 2,000 c.p.m. for a period of 3 hours, during 2 hours of which time the instrument is subjected to a pressure equal to 50 percent of its range. The amplitude of vibration of the pointer with respect to the dial is observed in the frequency range 1,000 to 2,000 c.p.m., while the instrument indicates the pressure of 50 percent of its range. Immediately following the vibration the scale errors are determined and compared with those previous to the vibration.

The total amplitude of vibration of the pointers of the pressure gages should not exceed 2 percent of the maximum range.

It appears that the Bourdon tube in a number of designs of fuel-pressure gages has a free frequency between 1,000 and 2,000 c.p.m., and consequently the

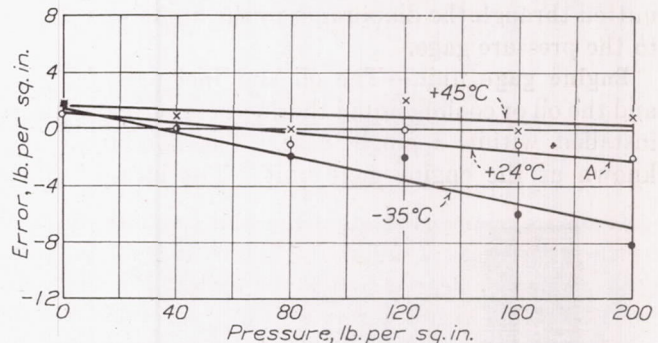


FIGURE 42.—Errors of oil-pressure gages at temperatures of +24°, +45°, and -35° C

pointers vibrate with an amplitude so large that fatigue failure of the Bourdon tube may be anticipated in service. This condition may be most easily remedied by the addition of an inertia disk to the pointer shaft, which, as pointed out in the section on Performance of Vapor Pressure Thermometers, reduces the free frequency and greatly reduces the amplitude of vibration at this frequency.

The average change in the scale errors due to a vibration of 3 hours should be negligible; that is, less than 1 percent of the maximum range.

Seasoning.—The seasoning test is made by subjecting the instrument to 100 applications of the pressure required to produce a deflection of the pointer corresponding to 50 percent of the range of indication. The scale errors before and afterwards are compared in order to determine the effects of seasoning.

The average change in the scale errors of good quality instrument should not exceed about 1 percent of the range, and are usually of the order of the least reading.

Drift.—In this test increase in reading of an instrument in a period of 1 hour is observed after it is suddenly subjected to, and held at, a pressure equal to 50

percent of its range in indication. This increase in reading is the drift, and in satisfactory instruments does not exceed 1 percent of the maximum range.

Suction and overpressure.—Pressure gages are likely to be subjected in service to pressures which are either below atmospheric pressure or exceed the range in indication. Their ability to withstand such treatment is determined in the suction and overpressure tests. The tests are made by subjecting an instrument first to a suction of 10 pounds per square inch for the oil pressure gage and 3 pounds per square inch for the fuel pressure gage, for a period of 1 minute, and, second, to a pressure 50 percent greater than the range in indication for a period of 10 minutes. The scale errors before and after the excess differential pressures are compared in order to determine the effect on the performance of suction and overpressure.

The average change in scale errors as a result of suction and overpressure does not usually exceed 1 percent of the maximum range.

Temperature errors.—The scale errors of the instrument are obtained with its temperature first at -35° and then at $+45^{\circ}$ C. The difference in the errors at these two temperatures is the effect of temperature.

The results of temperature tests on the typical oil pressure gage are also given in figure 42. The effect of temperature can be expressed as the difference in the slopes of the best straight lines for the data, divided by the temperature difference. This is the change in scale value per degree centigrade and is 0.044 percent for the temperature interval -35° to $+45^{\circ}$ C. for the instrument for which data is given in figure 42. The effect is due to the change in the modulus of elasticity of the Bourdon tube and the hair spring since the instruments are ordinarily uncompensated, and in poorly seasoned instruments due to unreleased internal stresses in the Bourdon tube. The temperature coefficient of the modulus of elasticity of bronze is about 0.040 percent per degree centigrade.

The effect of temperature may also be expressed in terms of the average of the change in error at each test point, which is 3.7 pounds per square inch for the data in figure 42.

B. ELECTRICAL PRESSURE GAGES

The performance of electrical pressure gages is determined by tests which are, in general, the same as those listed for mechanical pressure gages. In addition the resistance element should be subjected to vibration. The temperature test of the electrical pressure gage should include a scale error test in which the indicator is at room temperature and the pressure element is at the maximum temperature experienced in service.

Also the indicators must be tested for adequacy of magnetic shielding which should be such that an

aircraft compass is not deflected in excess of 4° when the distance between the two is 8 inches from center to center.

FUEL QUANTITY GAGES

The fuel quantity gage is used in aircraft to indicate the quantity of fuel available for continuing flight and is commonly installed in every modern aircraft. Although the amount of fuel remaining in the tank can be estimated from a knowledge of the rate of fuel consumption and the elapsed time, the possibility always remains that, due to leakage, less than this amount is available.

Fuel quantity gages are essentially of two types, one in which the position of a float in the liquid is indicated and the other in which the hydrostatic pressure of the head of the fuel is measured. In most cases a distant indicating instrument is essential.

Acceleration of the aircraft and deviation from the normal flying attitude of airplanes with shallow wing tanks cause errors equally in the two types.

The float-type gage is preferred when an indication at the tank is easily visible to the pilot. In the latter case the instrument is called a simple float type. The indicators are generally mechanically connected to the float, although in one design the coupling is made magnetically. The float type of instrument is relatively easy to install and reliable in operation.

The distant indicating float type is available in a great variety of designs (references 5 and 17) most of which have been produced in an effort to secure an instrument which is at the same time simple in design and dependable and accurate in operation. Distant indication has been secured (a) by a variety of mechanical connections, (b) electrically, and (c) by a hydrostatic device.

In the common design of the hydrostatic fuel quantity gage the head of the fuel is balanced by an air pressure which is measured by a suitable gage. The instrument is distant indicating. Other designs have been proposed in which the indication depends upon the pressure of the head of fuel, but these for various reasons have not proved practical.

SIMPLE FLOAT TYPE

In fuel quantity gages of this type the indication is obtained at the tank either below or above the float, whichever may be the most easily accessible to the pilot. The instrument consists of some form of indicating device connected to a cork or metal float resting on the surface of the fuel. A number of the designs which have been developed, are described below.

(a) The method of indication shown in figure 43 is especially useful in aircraft equipped with a fuel tank which is centrally located in the upper wing. As shown in the figure, the float is fastened to a disk by

means of a rod. The disk is visible through a glass tube graduated in terms of the quantity of fuel. One objection to this design is the possibility and consequences of breakage of the glass tube, which, however, has not been as frequent as might be expected.

(b) In the instrument shown in figure 44 the float is attached to the end of a long rod which rotates as the float falls with the level of the fuel. As is obvious from the figure, the rotation of the rod also causes rotation of the indicating drum by means of the sector and pinion mechanism.

(c) In a third type the float is mounted between guides which permit vertical movement but prevent rotation. A twisted metallic strip extends through a slot in the center of the float and is rotated by the float as the level of the fuel changes. A pointer attached to the twisted strip indicates on a suitable dial the quantity of fuel.

(d) In still another type, of which many are in use, the displacement of the float is transmitted to the

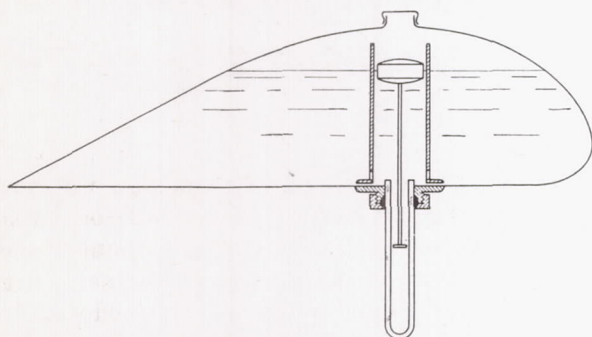


FIGURE 43.—Float type fuel quantity gage with indicator below tank.

indicator by means of a braided silk cord. One end of the cord is connected to the float and the other end is secured to a sheave mounted within the indicator. The cord is kept taut by means of a light spring mounted within the sheave. As the float drops with the level of the fuel the sheave is caused to rotate by the unwinding of the cord. Through a suitable gear and pinion the sheave operates a pointer which indicates the fuel quantity on a suitably engraved dial.

(e) **Boston gage.**—Stuffing boxes or similar shaft glands are eliminated by means of the magnetic method of indication which is used in the Boston gage. In this instrument a bar magnet is rotated by the float as it changes its level. The magnet is mounted inside and, coaxially, a magnetized pointer outside of the tank. Due to the magnetic force between the pointer and magnet the pointer aligns itself with the magnet and thus indicates the quantity of fuel.

DISTANT INDICATING FLOAT TYPE

Mechanical types.—The only distant indicating float type instrument with a mechanical transmission used in this country is the one in which a braided silk cord is used to connect the float with an indicating sheave,

similarly as described under (d) above. Outside of the tank the cord runs in tubing in which a roller is installed at each bend. In this instrument the number of bends in the line and the distance between the indicator and float must be kept to a minimum, as otherwise the friction is likely to be excessive. Further, it is difficult to design a stuffing box at the point where the cord comes through the tank so as to eliminate wetting part of the cord which passes through the tubing. When the cord is wet the friction is greatly augmented.

Considerable attention has been given abroad to the perfection of the mechanical transmission type. In

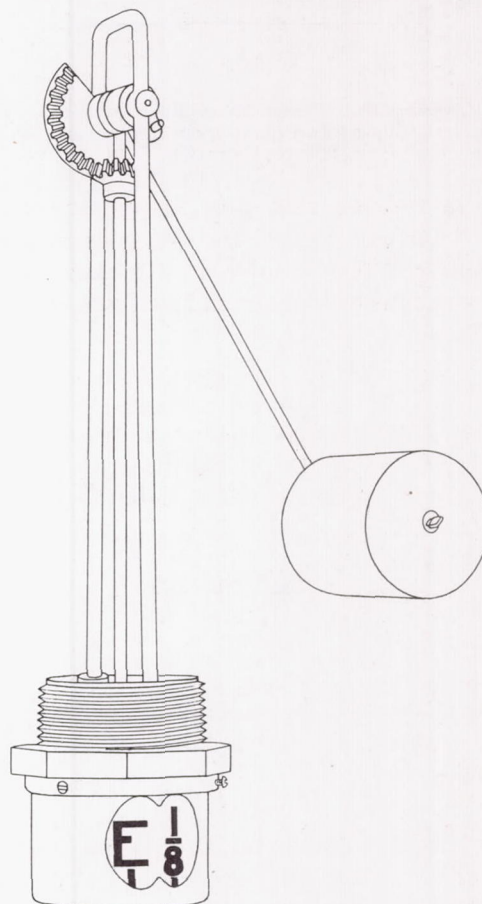


FIGURE 44.—Float and rod type fuel quantity gage.

one instrument (the Corset) the motion of the float causes longitudinal motion in the connecting line to the indicator, which consists of a series of short push rods connected to each other by means of a ball and cup arrangement. In two other instruments, the Televel and Spirobloc gages, the power to operate the indicator is furnished by the pilot. When a reading is desired, the pilot, by means of a wire connection to the tank element, either rotates or raises the float until a stop is encountered, which operation at the same time correspondingly varies the reading on an indicator. The point at which the stop is encountered, and thus the reading, depends on the level of the fuel. (See reference 17.)

Nagel gage.—An electrical transmission system is used in the Nagel gage. The float, mounted as shown in figure 44, governs the position of contact *S*, figure 45, which divides a resistance into two parts R_1 and R_2 .

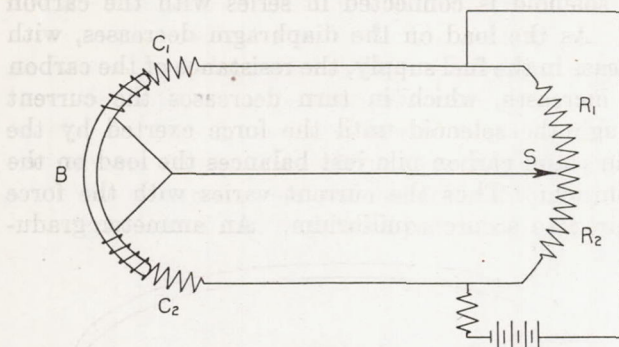


FIGURE 45.—Diagram of electric circuit of Nagel fuel quantity gage. The contact *S* is operated by a float, and the resulting change in current in C_1 and C_2 changes the position of equilibrium of the iron armature *B*.

Changes in resistance R_1 and R_2 affect the relative amount of current through the two coils C_1 and C_2 in the indicator. The pointer is attached through a suitable mechanism to a circular iron vane *B*, the posi-

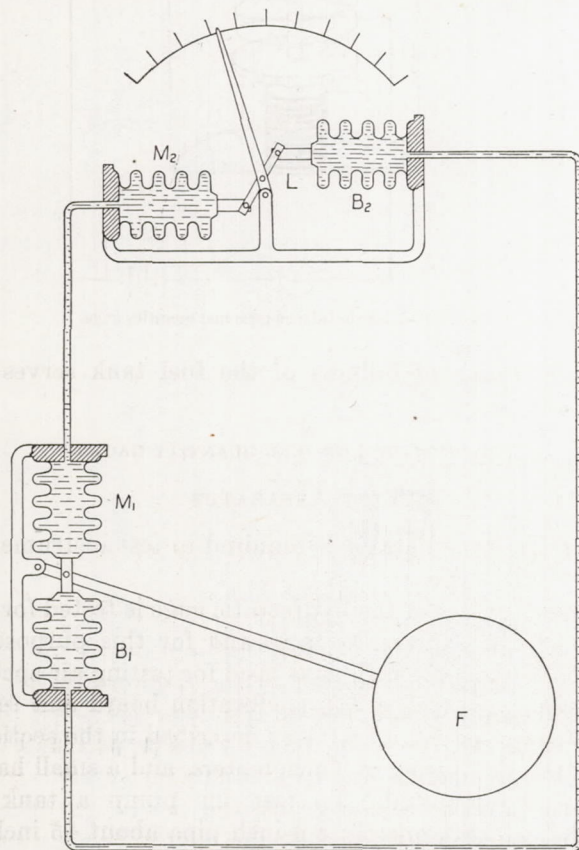


FIGURE 46.—Liquidometer fuel quantity gage.

tion of which varies with the relative amounts of the current through C_1 and C_2 . Since the indicator is in effect an ohmmeter, its indication is independent of the impressed voltage within a wide range. Although considerable attention has been given to the design of

a fireproof stuffing box between the resistances R_1 and R_2 and the fuel, a possible fire hazard remains.

Liquidometer.—In this fuel-quantity gage the deflections of the float are transmitted hydraulically through any desired length of line to the indicator. Referring to figure 46, float *F* is mechanically connected with two metallic bellows M_1 and B_1 each of which is in communication by means of copper tubing with another bellows, M_2 and B_2 , respectively, contained within the indicator. The two closed hydraulic systems thus formed are of approximately equal volumes and are filled with a suitable liquid having a low freezing point. The bellows M_2 and B_2 are connected together by means of link *L* which is pivoted at its center to the pointer. As the float falls, due to fall in the fuel level in the tank, B_1 is compressed and M_1 expanded, the resulting differential displacement of the liquid expanding B_2 and compressing M_2 , thus deflecting the pointer to the left. The design of link *L* permits

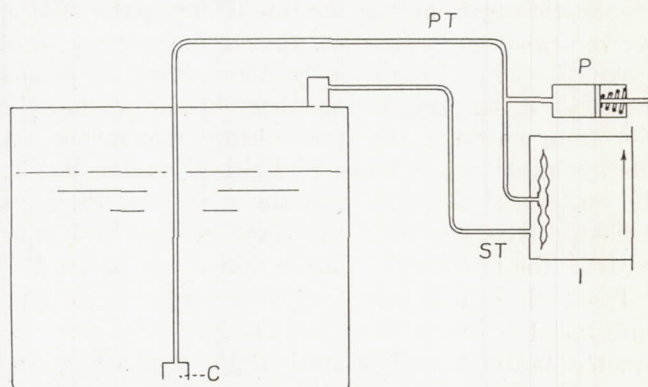


FIGURE 47.—Diagram of hydrostatic type fuel quantity gage.

changes in volume of the liquid due to changes in temperature without affecting the indication.

HYDROSTATIC FUEL-QUANTITY GAGE

Common type.—The essential parts of this instrument consist of an airtight pressure gage *I*, figure 47, a pump *P*, a pressure line *PT* leading from the interior of the diaphragm capsule to a cell *C* at the bottom of the fuel tank and a static pressure line *ST* leading from the case of the indicator to the top or the vent of the tank.

When the pump handle is pulled out against the action of a spring and permitted to return, the return stroke of the pump clears the entire line *PT* of liquid, the excess air passing into the liquid through openings in the cell *C*. The head of liquid *H* is now balanced at the cell *C* by the air pressure at this point, that is, by the air pressure in the line *PT* and the interior of the diaphragm. The static tube *ST* serves to maintain the interior of the indicator case at the pressure of the air above the fuel. The gage thus indicates the difference in these two air pressures or the pressure of the head of the fuel.

The indicator is made in a number of convenient ranges for use with tanks of differing depths. The cases are ordinarily of bakelite and are the standard 2 $\frac{3}{4}$ -inch dial size. The dials are calibrated after installation, as is almost necessarily the case with all fuel quantity gages. For test purposes temporary dials graduated in degrees of arc are usually furnished. The indicator has a restriction in the line to the diaphragm capsule in order to dampen out the effect of surges in the fuel. The weights of the pump and the indicating gage are 4 and 9 ounces, respectively. Connecting tubing of copper is commonly used.

The accuracy of the instrument is not affected by changes in the temperature of the air in the lines if the pump is operated before making a reading.

It is essential that the fuel be prevented from getting into the line insofar as possible. Fuel in the line PT up to the point where the pump is installed can be removed by means of the pump. Fuel in the line beyond this point and in the line ST or in the case of the indicator make the instrument inoperative until removed. Check valves at the point where the tubing connects to the tank may be desirable to prevent the fuel from entering the lines during maneuvers. A float-operated check valve is desirable in the line to the bottom of the tank. In the rare case when the indicator is colder than the fuel, condensation may occur in the indicator. This is difficult to prevent.

The fuel tank is sometimes vented to a modified pitot head which is mounted in the air stream, in which case the line ST is connected in such manner as to prevent fuel getting into it.

SUBMERGED CAPSULE TYPE

This instrument differs from the common hydrostatic gage in that the line PT connects to a diaphragm capsule in place of the cell C, figure 47, and in that the pump P is eliminated. In order to take care of changes in air pressure with altitude, and changes in temperature, the diaphragm capsule must be perfectly flexible so that the resulting volume changes in the contained air do not affect the indication. As in the case of the common type instrument the pressure of the air within the capsule differs from that above the liquid by that of the head of the liquid. A serviceable instrument has not as yet been obtained owing to the difficulty of obtaining a diaphragm material which has the required degree of flexibility and is at the same time dependable in operation.

G.E. ELECTRIC GAGE

An electrically operated hydrostatic fuel quantity gage which has been developed is of interest (reference 56), although it is not at present being manufactured. In the instrument, shown diagrammatically in figure 48, the head of the fuel is for the most part balanced

magnetically by a solenoid which is energized by means of a storage battery. The pressure of the head of the fuel is transmitted through a diaphragm to the plunger of the solenoid and a carbon-pile rheostat. The solenoid is connected in series with the carbon pile. As the load on the diaphragm decreases, with decrease in the fuel supply, the resistance of the carbon pile increases, which in turn decreases the current through the solenoid until the force exerted by the plunger and carbon pile just balances the load on the diaphragm. Thus the current varies with the force required to secure equilibrium. An ammeter gradu-

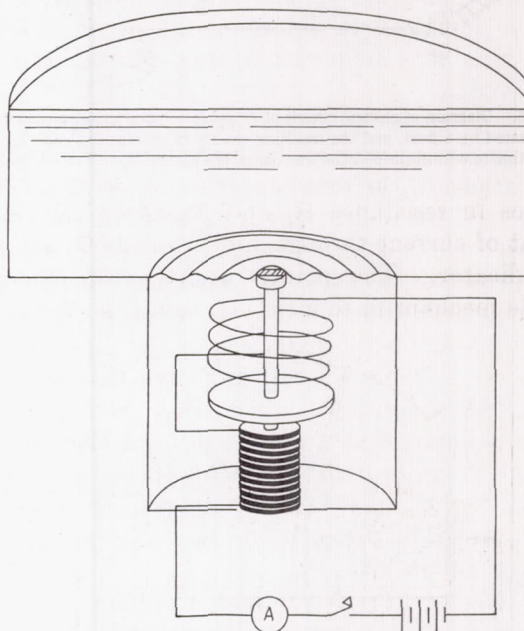


FIGURE 48.—Electric balance type fuel quantity gage.

ated in terms of fullness of the fuel tank serves as the indicator.

PERFORMANCE OF FUEL QUANTITY GAGES

TEST APPARATUS

No special apparatus is required to test instruments of the float type.

The indicator of the hydrostatic gage is tested for its accuracy as a pressure gage, and for this purpose a water manometer such as is used for testing air-speed-indicators (reference 33), a vibration board and temperature-control apparatus as described in the section, Laboratory Testing of Tachometers, and a small hand pump are required. To test the pump a tank is needed which is merely a 4-inch pipe about 45 inches long, closed at one end. Water is used to fill it.

Although the submerged capsule and electric gage types have not been tested at the Bureau of Standards, it appears that the only special test equipment required in addition to that noted above is a tank of somewhat larger cross-section and perhaps a little deeper.

SIMPLE FLOAT TYPE

In the cases where this type of gage can be used, no trouble is experienced in securing sufficient accuracy and dependability of operation. It is a simple matter to determine whether or not the pointer motion is sufficient for the range of motion of the float and that excessive friction is not present in the mechanism.

DISTANT INDICATING FLOAT TYPE

(a) *Mechanical transmission.*—The presence of excessive friction and the scale errors can be determined by operating the instruments in a laboratory. Service tests are necessary to determine performance factors such as reliability in operation, ease of installation, and ease of repair.

(b) *Performance of Nagel gage.*—Laboratory tests show that the reading of the instrument is unchanged for variations in the rated applied voltage of about 20 percent; that the indications are affected on the average less than 4 percent for a change in temperature of 50° C. of either the indicator or resistance unit; that, for one unit tested, an explosive mixture of acetylene and air maintained on the tank side of the tank unit was not ignited. The latter test indicated that either the stuffing box prevented the gas from getting into the housing of the resistance unit or, if it did, that sparking sufficient to ignite it did not take place. Due to the possible fire hazard it is recommended, however, that the instrument be connected to the battery only when a reading is desired.

(c) *Liquidometer.*—No data are available on the performance of this instrument. It is just being adapted for aircraft use.

HYDROSTATIC GAGE

Common type.—The indicator of this fuel quantity gage is given tests to determine its accuracy as a pressure gage similar to those given air-speed indicators. The tests for the latter are described in reference 20 and will not be described in detail here. The mechanism of these indicators is similar and the range of pressures for which they indicate are of the same order of magnitude. Test results for a typical indicator show that the effect of friction in the mechanism, the drift, and changes in calibration due to seasoning are negligible. Tipping the instrument 90° from the normal operating position causes a change of about 2° of arc; the total amplitude of vibration of the pointer when the instrument is subjected to the standard vibration, and the change in scale errors afterwards, does not exceed 2° of arc; and the maximum difference in reading at any point on the scale for a temperature change from +45° to -35° C. does not exceed about 6° of arc.

The case of the indicators must be leak tight against pressure differences which are estimated not to exceed 10 inches of water.

It is essential that the capacity of the pump be sufficient, under the most unfavorable conditions, to clear the pressure line and the hydrostatic cell of fuel. To test its capacity, the pump is connected by 20 feet of standard tubing to a hydrostatic cell, having an internal volume approximately equivalent to that of the cell C, figure 47. The cell, but not the excess tubing, is submerged in a tank of water to a depth of 40 inches. The pump capacity is deemed ample when one stroke is sufficient to clear the cell and 40 inches of tubing of water which is made evident by bubbles of air rising to the surface. The design of the pump must be such that the forward stroke causes but little suction in the tubing and a forcible return does not give rise to a pressure great enough to harm the indicator.

FUEL-FLOW INDICATORS

Fuel-flow indicators may be classified as follows:

(a) Flow meters which indicate the rate at which the fuel is flowing to the carburetor.

(b) Fuel consumed meters which indicate primarily the quantity of fuel consumed. The rate of fuel consumption can be determined with the use of a stop watch.

(c) Combustion indicators which indicate the extent to which all of the available energy is being obtained from the fuel.

A fuel-flow meter or a combustion meter is useful in adjusting the air-fuel mixture ratio so as to obtain the most economical rate of fuel consumption. A reduction in operating costs and an increase in the cruising radius are two of the advantages gained. Tests have shown that in some cases with the aid of a fuel-flow meter as much as one third of the total amount of fuel consumed may be saved if the mixture ratio is carefully adjusted (reference 55). Due to the fact that an entirely satisfactory instrument has not as yet been developed, the instrument has not come into general use.

The fuel-consumed meter is used in flight tests to measure rate of fuel consumption under various conditions. As time must be measured to determine the rate of flow, the instrument finds little favor in general service.

The first two types can be used with engines in which free-flowing fuels, such as aviation gasoline, are used. The combustion indicator is suitable for use with any type of fuel, including heavy oil.

Fuel-flow meters are either of the venturi or the variable-orifice type. The venturi instrument is an adaptation of the venturi flow meter commonly employed in hydraulic engineering work. The variable-orifice types have been developed in England, the most promising of which is a refinement of the well-known sink and tube type flow meter.

Flow meters for service use on aircraft, and also fuel-consumed meters insofar as they are useful, should have the following ideal characteristics:

(a) They should be designed to have the minimum interference with the fuel supply to the engine. An easily operated bypass, preferably automatic, should be provided for use either in case of failure of the instrument in service or stoppage of the line in case all the fuel flows through the flow meter.

(b) The indicator should be on the instrument panel and be of a type such that no fuel lines need be brought up to the instrument panel. The method of distant indication should be such that the flow meter can be used on multi-engined aircraft.

(c) If possible, the indicator should conform in size and shape to existing service instruments.

(d) The instrument should not add to the fire hazard.

(e) The instrument should not require frequent priming to eliminate air or other gases from the lines leading to the indicator. This procedure is necessary in the ordinary venturi type.

(f) If other requirements are met, an over-all error as great as 5 percent may be tolerated in flow meters for general service use.

FUEL-FLOW METERS

VENTURI TYPE

A diagram of the venturi fuel-flow meter is shown in figure 49. The parts consist of a venturi tube, a differential pressure gage, and connecting tubing. The venturi tube is inserted in the fuel line leading to the carburetor and, as is shown in the figure, is connected with the indicator by means of two copper tubes of small bore.

One tube connects the throat section of the Venturi tube with one side of the diaphragm, or, more exactly, to the interior of a diaphragm capsule, and the other connects the entrance section of the Venturi to the case of the indicator. When fuel flows the fuel pressure is less at the throat section than at the entrance, which difference is indicated by the gauge.

The differential pressure developed by the Venturi tube (reference 53) can be obtained by means of Bernoulli's theorem, which may be stated as follows: The total energy of a liquid flowing in a pipe is equal at one point, if frictional effects are neglected, to the total energy at any other point. If the pipe is horizontal, the theorem may be expressed mathematically as follows:

$$\frac{P_1}{D} + \frac{V_1^2}{2g} = \frac{P_2}{D} + \frac{V_2^2}{2g} \quad (16)$$

where P_1 and P_2 are the static pressures, and V_1 and V_2 the velocities at the points 1 and 2, respectively. D is the density of the liquid and g the acceleration of gravity.

Substituting $\frac{Q}{a_1}$ for V_1 , $\frac{Q}{a_2}$ for V_2 , and P for $P_1 - P_2$ in the above expression there is obtained

$$Q = \sqrt{\frac{2gP}{D} \frac{a_1 a_2}{\sqrt{a_1^2 - a_2^2}}} \quad (17)$$

Here Q is the average volume rate of flow, and a_1 and a_2 the cross-sectional areas of the pipe at points 1 and 2 respectively.

Applying equation (17) to the Venturi tube, the last term, designated M , is called the geometrical constant of the Venturi tube since it depends only upon the areas of the entrance and throat sections. Rearranging

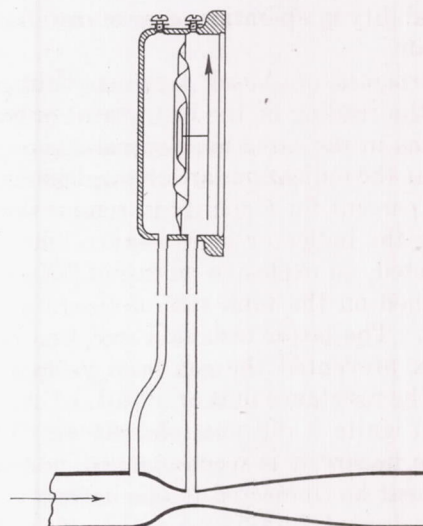


FIGURE 49.—Venturi type fuel-flow meter.

equation (17) and substituting M for its equivalent there results

$$P = \left(\frac{Q}{M} \right)^2 \frac{D}{2g} \quad (18)$$

Inspection of equation (18) shows that the differential pressure P increases as the geometrical constant M decreases. A large value of P is desirable in order to permit the use of as rugged an indicator as possible. A small value of M is obtained when the area a_2 of the throat section is small compared with the area a_1 of the entrance section. Referring again to equation (18) it may be seen that an error in indication is introduced by deviations of the density of the fuel from the value used in calibrating the instrument. For small changes in the density of the fuel the reading of the instrument at a given volume rate of flow increases one half percent for each 1 percent increase in the density.

There is considerable objection from the viewpoint of safety of the pilot in an accident to having fuel at the instrument board. In the ordinary instrument the case

is completely filled with fuel and the cover glass is required to retain it under the pressure of the fuel pump. As a further safeguard the Bureau of Standards has recently developed for the Bureau of Aeronautics of the Navy Department an indicator which contains two pressure-sensitive capsules. The venturi tube is connected to the interior of the capsules, and fuel therefore does not fill the case of the indicator. The arrangement of the mechanism is such that it is practically insensitive to variations in the pressure developed by the fuel pump, but is responsive to variations in the differential pressure developed by the venturi tube.

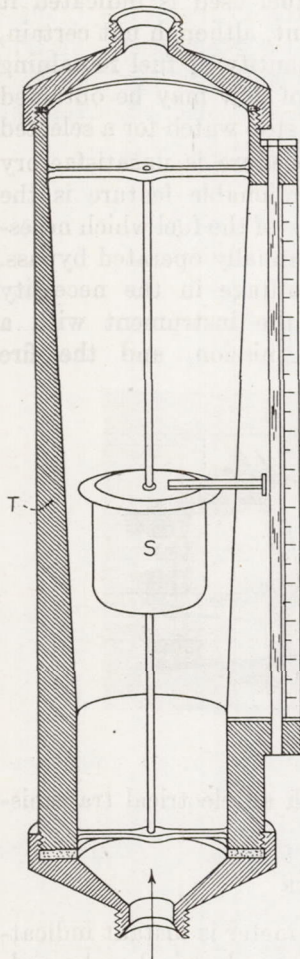


FIGURE 50.—Orifice and sink type fuel-flow meter.

the differential pressure developed by the venturi tube.

VARIABLE ORIFICE FLOW METER

A diagram of the variable orifice fuel-flow meter as modified by Griffith (reference 55) is shown in figure 50. Referring to the figure, a sink *S* having a knife-edged disk for its upper surface, is free to move vertically along the axis of a tapered tube, *T*, being guided in its movement by a central post. The sink carries a pointer to indicate its position with reference to a scale graduated in weight of fuel per hour and affixed to the body of the tube. Fuel entering the lower end of the instrument raises the sink until its weight is balanced by the dynamic pressure of the fuel against it. The fuel passes through the annular orifice between

the edge of the disk and the tapered tube and then out through the upper end of the instrument to the carburetor. It follows that the drop in pressure across the instrument is constant.

When the rate of flow of fuel is constant the sink is suspended in equilibrium by a system of forces related as follows:

$$\frac{1}{2} D_f V^2 = \frac{W_a}{A} \quad (19)$$

where D_f is the density of the fuel, V the velocity of the fuel through the orifice, W_a the weight of the sink when submerged in the fuel and A the area of the disk. In this equation the left-hand member represents the dynamic pressure exerted upward against the under side of the sink. The right-hand member represents the downward pressure due to the weight of the submerged sink

However,

$$W_a = gv(D_s - D_f) \quad (20)$$

where v is the volume and D_s the density of the sink. Substituting this value of W_a in equation (19) and solving for V ,

$$V = \sqrt{\frac{2gv(D_s - D_f)}{AD_f}} \quad (21)$$

The equation for the mass rate of flow through an orifice is as follows:

$$M = KaVD_f \quad (22)$$

where M is the mass rate of flow of the fuel, K the discharge coefficient, and a the area of the orifice.

Substituting for V from equation (21)

$$M = Ka\sqrt{\frac{2gv(D_s - D_f)D_f}{A}} \quad (23)$$

Since the vertical displacement of the sink determines a , the area of the orifice, it is also a measure of the mass rate of flow M .

Inspection of equation (23) shows that, for a given mass rate of flow the reading of the instrument, which is proportional to a , and the densities of the fuel and sink have the following relation:

$$\frac{1}{a} \propto \sqrt{(D_s - D_f)D_f} \quad (24)$$

In order that there be a minimum change in the reading with variations in D_f , it is necessary that the derivative with respect to D_f of the right-hand member of the equation (24) equal zero. This is the case when $D_s = 2D_f$; that is, when the density of the sink is twice the density of the fuel. If this relation holds for one density of the fuel, the error in indication is only 0.8 percent for a variation of 12 percent in the fuel density.

Up to the present the instrument is stated to be useful only in flight testing. It is not used on service airplanes mainly because of the added complication in installing and maintaining the fuel lines and partly

because of the difficulty of finding suitable place to install an instrument of such an unusual shape. In common with other types of flow meters, all of the fuel must pass through the instrument and therefore close to the pilot, which, in view of the window entails an extra hazard in case of accident. The fuel just ahead of the instrument must be filtered, since it is sensitive to minor obstructions in the flow. A bypass is usually provided.

VANE TYPE FLOW METER

In the R.A.E. (British) vane type flow meter, the pressure of the flowing fuel upon a rotatable vane is balanced by the action of a spring (references 5, 11, and 17). The axis of the vane is offset from that of its case, so that the space between the case and the vane, or orifice, varies with the position of the vane. In effect it is a variable orifice, variable pressure drop type instrument.

Difficulties are experienced in obtaining the same state of turbulent flow under all conditions of use.

charge of the fuel to the individual cylinders. Some form of revolution counter is attached either directly to the wobble plate shaft or indirectly by means of a flexible drive shaft.

The fuel-consumed meter is highly accurate (in instruments available the error does not exceed 0.01 gallon per gallon of fuel delivered). It is readily installed by inserting it at any convenient point in the fuel line between the fuel pump and the carburetor. Since the total quantity of fuel used is indicated it may be used as an independent, although not certain, means of determining the quantity of fuel remaining in the tank. Average rates of flow may be obtained by measuring the time with a stop watch for a selected volume of flow, but this procedure is unsatisfactory in general service. An objectionable feature is the danger of restriction to the flow of the fuel which necessitates the installation of a manually operated bypass. There is the further disadvantage in the necessity for tight stuffing boxes in the instrument with a mechanical method of transmission, and the fire

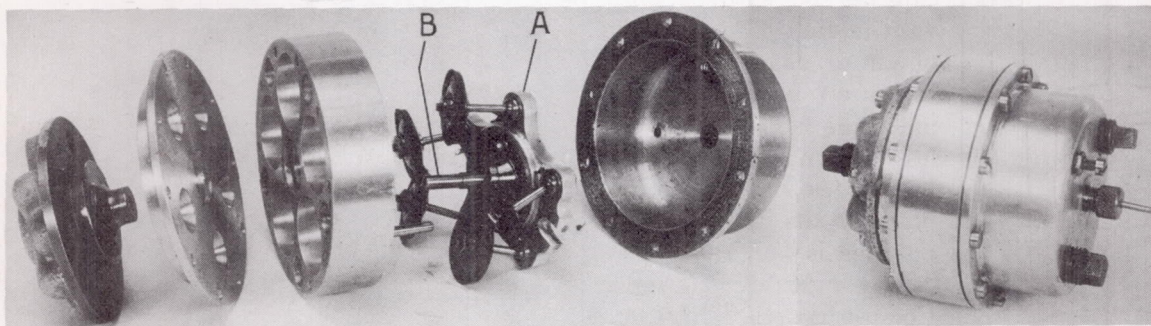


FIGURE 51.—“Western” fuel-consumed meter.

Bubbles of gas in the fuel, which appear with increase in the altitude of flight, affect the readings. The above two difficulties appear to be inherent so that the instrument remains an experimental type. As the force on the spring varies as the square of the rate of flow, the force decreases rapidly with the rate of flow, so that low rates cannot be measured.

FUEL-CONSUMED METERS

The fuel-consumed meter is essentially a displacement pump equipped with a counting device for integrating the revolutions of the pump shaft. The counting device is usually graduated in terms of volume of fuel flowing through the pump. Pump units usually have five cylinders with their axes parallel and arranged symmetrically around the shaft.

A design typical of the fuel-consumed meter is shown in figure 51. The five pistons are connected to wobble plate A which is pivoted to shaft B by means of a large ball bearing set at an angle to the shaft. With this arrangement the reciprocating motion of the pistons causes the shaft, to rotate. A valve plate which is rotated by the shaft controls the delivery and dis-

charge of the fuel to the individual cylinders. Some form of revolution counter is attached either directly to the wobble plate shaft or indirectly by means of a flexible drive shaft.

BOWSER

The Bowser fuel consumed meter is distant indicating. The pump unit includes an electrical make-and-break mechanism which is connected to the wobble plate shaft and is submerged in transformer oil in order to eliminate the danger from sparking. The indicator unit consists of a counter operated by a solenoid the electrical circuit of which is interrupted by the make-and-break mechanism. The power is furnished by a 12-volt battery or its equivalent. The pump capacity is such that every time the solenoid is energized, which is twice in every revolution of the wobble plate shaft, 0.01 gallon of fuel is delivered. One hand of the counter makes one revolution for each gallon of fuel consumed and indicates by steps of 0.01 gallon. Another hand is provided which rotates once for each 10 gallons. A pressure varying from 0.25 to 0.50 pounds per square inch is required to operate the pump unit. The weights of the pump unit and revolution counter are 9% and 1% pounds, respectively.

WESTERN

In this instrument, which is shown in figure 51, the pistons are made of leather cup washers. The indication is secured by means of a small revolution counter attached to the wobble plate shaft. The weight of the pump unit is $2\frac{1}{4}$ pounds.

COMBUSTION INDICATOR

It is obvious that the most economical functioning of the engine is obtained when the amount of the combustible gases in the exhaust is relatively small. The Moto Vita combustion meter (reference 57) indicates the energy available in the unburned gaseous products in the exhaust of the engine.

The instrument is based upon the catalytic property of heated platinum to cause chemical combination, or combustion, upon its surface of a mixture of combusti-

regulator is used to compensate for variations in the voltage supply.

The exhaust gases consist principally of methane (CH_4), carbon monoxide (CO), hydrogen (H_2), and more complex compounds. In burning, these gases liberate widely varying amounts of energy per molecule and thus the heating of the exposed wires depends upon the composition as well as the amount of the combustible gases. The instrument therefore indicates only the latent calorific value of the energy remaining in the exhaust.

The combustion indicator indicates the efficiency of combustion without regard to any design characteristics of the engine, viz, speed, power, etc., is distant indicating, requires no modification of the fuel line for its installation, and is applicable to heavy-oil engines as well as those burning lighter fuels.

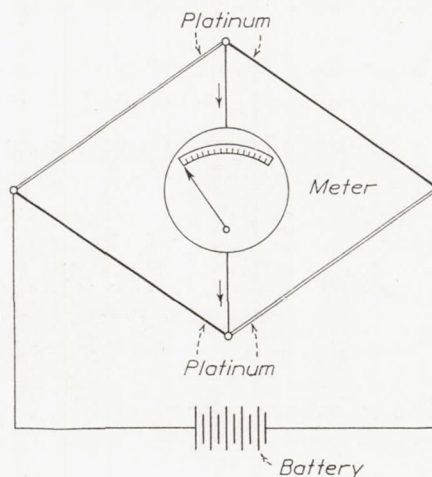
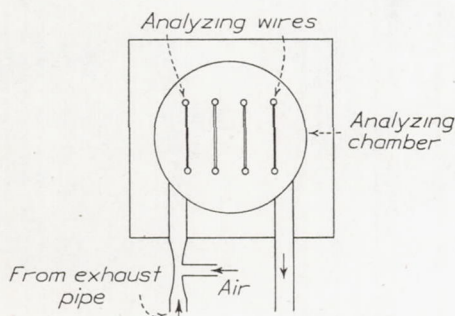


FIGURE 52.—Diagram of combustion indicator.

ble vapors and oxygen. It is essentially an unbalanced Wheatstone bridge an electrical diagram of which is shown in figure 52. It has three parts—the combustion element, the indicator, and a battery. The four platinum wire resistances of the Wheatstone bridge are mounted in the combustion element, or analyzing chamber, so that a constant-ratio mixture of exhaust gas and air passes over them. Two of the wires are protected from the exhaust gases by means of tubing, presumably glass. All of the wires are heated electrically, including the nonactive wires, in order to avoid errors due to differences in temperatures. Since all four legs of the bridge are mounted in the analyzing chamber and are therefore at the same temperature, as long as only noncombustible gases are present, their resistances increase equally and the circuit remains in balance. Upon the admission of a mixture of a combustible gas and air, combustion occurs only on the surface of the bare wires, which increases their temperature, and consequently their resistance, over that of the covered wires of the bridge. A ballast type voltage

LABORATORY TESTING OF FUEL-FLOW INDICATORS

APPARATUS

The apparatus used in the calibration of fuel-flow meters and fuel consumed meters consists of an elevated tank, a graduated flask, a supply tank, and a return pump driven by an induction motor. The instrument is connected at a point in the copper tube line from the elevated tank to the graduated flask so as to be subjected to the desired head of liquid. The fuel flows under gravity from the elevated tank, through the instrument being tested, and then into the graduated flask from which it is dumped into the supply tank. The pump then returns the fuel to the reservoir. In practice the pump is operated continuously, so that, regardless of the rate at which the fuel is passing through the instrument, practically a constant head of fuel is maintained in the reservoir, the excess fuel being conducted to the supply tank through an overflow pipe. At each test point the average volume rate of flow is fuel is obtained by measuring with a stop watch the

time required for a definite quantity of fuel to flow into the measuring flask. The rate of flow is controlled by means of a variable orifice.

TESTS

Up to the present, tests on flow meters, fuel-consumed meters, and combustion meters have not been standardized, nor have they been developed so as to determine the performance of the instruments under all of the conditions of use on aircraft. Development of these tests for flow meters has not been justified in view of (a) the large gap between the ideal characteristics and the actual performance and (b) the consequent fact that the instruments are used but little. Fuel-consumed meters have a fine performance in most respects but are little used on aircraft mainly because they do not indicate directly either the fuel flow or fuel quantity available, and partly owing to the somewhat unsatisfactory design of the mechanism for securing distant indication. Combustion indicators are highly experimental with respect to their usefulness and appear, in the present design, to be insufficiently rugged for service use on airplanes.

Only the primary tests on flow meters and fuel-consumed meters will be described.

Scale error.—The scale errors of both fuel flow meters and fuel-consumed meters are determined by means of the apparatus described above. The scale error of the instrument under test is the difference between its reading and the average rate of flow. The liquid used should have very nearly the density of that used as the standard in calibrating the instrument, otherwise a correction must be made based on the experimentally determined effect of the variation from this density.

Density effect.—The effect of variation in the density of the fuel is determined by scale error tests in which two or three fuels, or equivalent liquids of various densities, are used successively. Since the effect of changes in density is predicted theoretically for most available types of flow meter, and is presumably zero for the fuel-consumed meter, the test needs to be made only once on each type in order to establish the validity of the predicted effect.

Pressure error.—The effect of variation of fuel pressure on the reading of an instrument is obtained from scale error tests in each of which the instrument is subjected to a different head of liquid. These heads are within the extremes of pressure which may occur in service. It is obvious that the effect should be negligible within small limits for both flow meters and fuel-consumed meters.

Other tests.—The power to operate, or the pressure drop across, fuel-consumed meters must be reasonably small in comparison with the ordinary value of fuel

pressure. Further their reading should be independent, within reasonable limits, of the rate of flow.

In addition to the above tests, flow meters and fuel-consumed meters should conform to the usual requirements for aircraft instruments relative to (a) freedom from position error, (b) vibration effects and (c) operation in the temperature range which may be experienced. The tests for these errors are similar in nature to those described for pressure gages or tachometers.

MANIFOLD PRESSURE GAGES

Supercharging is accomplished either (a) by increasing the pressure of the air entering the carburetor or, more commonly, (b) by increasing the pressure of the fuel-air mixture after it leaves the carburetor and before it reaches the engine. In order to control the amount of supercharging it is necessary for the pilot to know the absolute pressure of the air or fuel-air mixture after leaving the supercharger. The instrument used to indicate this pressure is now known as a "manifold pressure gage", but until 1933 was called a "supercharger pressure gage."

In case method (a) is used, the fuel pressure must be in excess of the supercharger outlet pressure and the installation of the fuel pressure gage must be such that this excess is indicated. This is accomplished by making the case of the fuel pressure gage airtight and connecting it to the carburetor. This type of fuel pressure gage and the supercharger gage are sometimes combined to form a unit known as a "supercharger gage unit."

DESCRIPTION OF GAGE

The manifold pressure gage is essentially an aneroid altimeter with a leak-tight case. As shown in figure 53, the instrument contains a diaphragm capsule, which is evacuated, and a suitable mechanism for multiplying its deflections. As is now the usual practice in this country, the diaphragm capsule is without a restraining spring, except for the hairspring. The range of the latest instrument is from 10 to 50 inches of mercury of absolute pressure. Instruments constructed before 1933 were calibrated in altitude units with a range, as shown in figure 53, from -10,000 to +20,000 feet (13.75 to 42.45 inches of mercury). As knowledge of the absolute pressure is required, the dial is nonadjustable, in contrast with that of the altimeter. In the latest design an adjustable dial, visible through a circumferential slot in the main dial, is provided in order to indicate permanently the allowable degree of supercharging for the particular engine. The inside of the case is connected by means of metal tubing to the intake manifold of those engines in which the fuel-air mixture is compressed and to the carburetor of those in which only the air passes through the supercharger.

Since the accuracy required of the manifold pressure gage is not as great as in the case of the altimeter, its construction from this angle presents no great difficulty. The case is specified to be leak tight and strong enough to withstand a pressure above atmospheric of

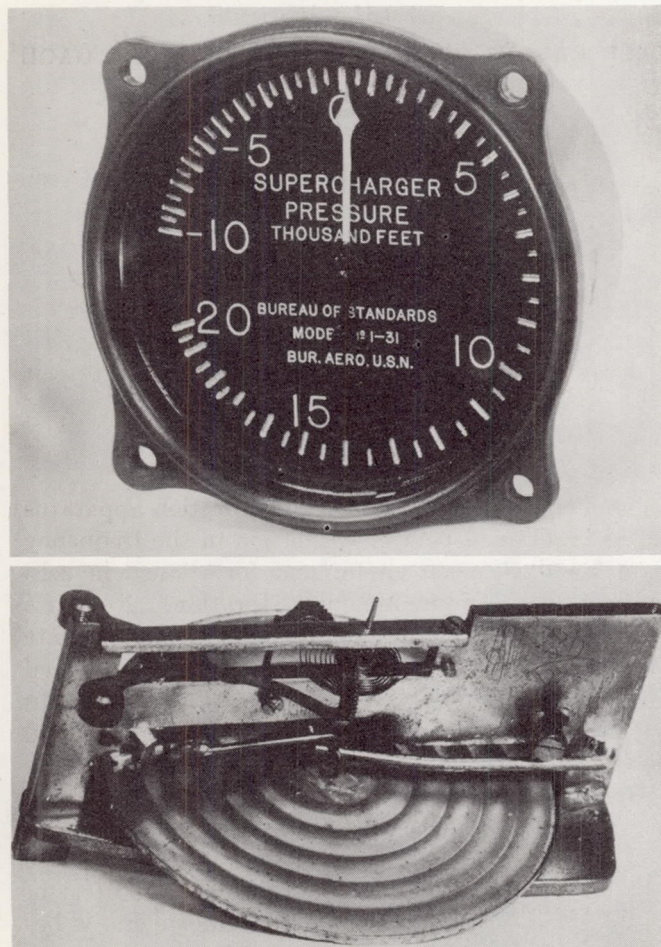


FIGURE 53.—Manifold or supercharger pressure gage.

20 pounds per square inch. Cover glasses one eighth inch thick and of the diameter required have been found on the average to withstand a differential pressure of over 25 pounds per square inch. It is further necessary to design the diaphragm capsule and mechanism to withstand reasonable pressures above and below the range. Surges in the pressure within the instrument case are greatly minimized by the insertion of a capillary tube in the fitting attached to the case. This is accomplished most simply by threading the hole in the fitting and inserting a machine screw to the proper depth.

The case of the instrument is of the standard 2 1/4 inch dial size and is usually made of a phenol condensation product. The instrument weighs 9 ounces.

APPARATUS FOR TESTING GAGES

The apparatus required to make the scale error test is shown diagrammatically in figure 54. A hand

pump *P* is used to obtain pressures above atmospheric and a vacuum pump *S* to obtain those below atmospheric. The difference in height of the mercury columns of the manometer is measured at each test point. To obtain the absolute pressure requires in addition the value of the atmospheric pressure which requires reading a mercurial barometer.

The heights of the mercury column of the manometer and barometer must be corrected for scale error and reduced to the standard conditions of temperature and acceleration of gravity. It is assumed that the scale errors are either negligible or known. The reduction to standard temperature can be made by subtracting 16×10^{-5} mm per mm (or inch per inch) of height of column for every degree centigrade the manometer or barometer is above 0° C. The reduction to the standard value of the acceleration of gravity can be made by subtracting 8×10^{-5} mm per mm (or inch per inch) of height of column, for each degree of latitude the station is below 45 degrees. Similarly when the latitude exceeds 45 degrees this amount is added. The above constants are first order approximations which are sufficiently accurate for use in testing supercharger pressure gages. The absolute pressure when above atmospheric, is obtained by adding the corrected height of the manometer mercury column to the corrected barometer reading, and when below atmospheric, by subtracting it from the barometer reading.

For gages calibrated in altitude units the altitude in the standard atmosphere corresponding to the pressure is then obtained from convenient tables. The

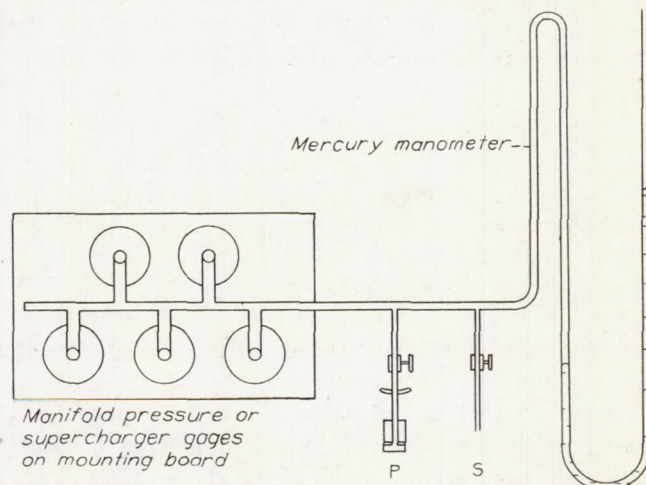


FIGURE 54.—Apparatus for testing manifold or supercharger pressure gages.

standard altitude-pressure table (reference 9) is given in table II.

It should be noted that other procedures may be followed in reducing the column heights to those under standard conditions. Tables of the corrections such as those given in the Smithsonian Meteorological Tables are preferred by most observers.

TABLE II

ALTITUDE-PRESSURE TABLE FOR CALIBRATING
MANIFOLD PRESSURE GAGES

Altitude, feet	Pressure		Altitude, feet	Pressure	
	Mm of mercury	Inches of mercury		Mm of mercury	Inches of mercury
-10,000	1,078.1	42.44	6,000	609.9	23.98
-9,000	1,042.2	41.03	7,000	586.4	23.09
-8,000	1,007.2	39.65	8,000	564.4	22.22
-7,000	973.1	38.31	9,000	543.2	21.38
-6,000	940.0	37.01			
-5,000	907.8	35.74	10,000	522.6	20.58
-4,000	876.6	34.51	11,000	502.6	19.79
-3,000	846.1	33.31	12,000	483.3	19.03
-2,000	816.6	32.15	13,000	464.5	18.29
-1,000	787.9	31.02	14,000	446.4	17.57
			15,000	428.8	16.88
0	760.0	29.92	16,000	411.8	16.21
1,000	732.9	28.86	17,000	395.3	15.56
2,000	706.6	27.82	18,000	379.4	14.94
3,000	681.1	26.81	19,000	364.0	14.33
4,000	656.3	25.84	20,000	349.1	13.75
5,000	632.3	24.89			

A standard for measuring the pressure more convenient and logical than the manometer and barometer combination is an altitude mercurial barometer in which the tube and scale are made long enough to measure also the pressures above atmospheric.

For determining the scale errors at airports or other field stations, apparatus similar to that shown in figure 54 is required except that the mercury manometer is eliminated. A calibrated manifold supercharger or pressure gage is used as the standard and is installed on the mounting board together with the instruments under test.

The temperature chambers and vibration board for testing the gages for the effect of temperature and vibration are similar to those described in section A of Laboratory Testing of Tachometers.

PERFORMANCE OF GAGES

The scale errors of a manifold pressure gage are determined by comparing its reading at a number of points over the range of indication with the pressures determined by means of a mercury monometer and barometer or its equivalent. The readings are made while the pressure is held constant both for decreasing and increasing pressures.

GAGE CALIBRATED IN ALTITUDE UNITS

The results of a scale error test made on a high quality instrument calibrated in altitude units as shown in figure 53 are given in table III, in which a positive sign means that the instrument reads too high and a negative sign, too low. It should be noted that the least reading of the instrument is 50 feet and that the highest accuracy is required at and near zero altitude, at which point a reasonable tolerance is an error of 250 feet.

The effect of changes in temperature of the gage upon the scale errors is obtained in tests made at $+45^{\circ}$ C. and -35° C. The scale errors at these tempera-

tures of the instrument referred to above are given in table III. The average change in reading in this temperature interval is 310 feet, for which a reasonable tolerance is 350 feet. The change in reading at zero altitude should be small, not exceeding about 200 feet.

TABLE III

SCALE ERRORS OF A MANIFOLD PRESSURE GAGE

Standard altitude, feet	Scale errors, in feet, at—		
	$+30^{\circ}$ C.	$+45^{\circ}$ C.	-35° C.
-10,000	-150	-100	-100
-6,000	0	+100	-50
-4,000	0	+150	-100
-2,000	0	+150	-150
-1,000	-50	+50	-100
0	0	+50	-100
1,000	+50	+50	-150
2,000	0	0	-150
4,000	0	0	-250
6,000	-50	+50	-300
8,000	0	+150	-250
10,000	0	+50	-300
12,000	+100	+200	-300
16,000	+50	+300	-400
20,000	0	+200	-600

The instrument is tested on the vibration apparatus for the amount of pointer oscillation in the frequency range 1,000 to 2,000 c.p.m. and for change in zero reading resulting from 3 hours' vibration. No parts should work loose. The pointer should not oscillate with respect to the dial more than an amount equal to about 200 feet. The change in reading at zero altitude of good quality instruments does not exceed 100 feet, or twice the least reading.

The damping of the instruments has been found to be satisfactory if the time for the reading to change from 20,000 to 5,000 feet, when the inside of the case initially at a pressure corresponding to 20,000 feet of altitude is suddenly opened to the atmosphere, is between 1 and 2 seconds.

The instruments may be subjected in service to differential pressures equal on one hand to those of the maximum altitude of flight of the aircraft and on the other hand to positive pressures, owing to surges, in excess of that corresponding to -10,000 feet of altitude. Their effect on the calibration should be negligible. As outside practical limits, absolute pressures of 7 and 25 pounds per square inch are selected. The instrument is given scale-error tests before and after being subjected to these pressures and has been found to have average changes in scale errors within the least reading or 50 feet.

The position error is the change in reading of the instrument when it is oriented from the normal position of dial vertical and pointer vertical to any other position. This change does not exceed the least reading, or 50 feet, in well-balanced instruments.

The case of the instrument must be leak tight against the difference in pressures corresponding to that between altitudes of -10,000 and +20,000 feet.

The instrument case should, as a safety provision, withstand a differential pressure greatly in excess of that corresponding to the pressure range of the instrument. The cases are made to withstand while subjected to vibration a pressure of 20 pounds per square inch. Sample cases without the mechanism are tested and are considered satisfactory if leak tight after the application of the pressure.

GAGE CALIBRATED TO READ PRESSURE

The manifold pressure gage calibrated to read in units of pressure from 10 to 50 inches of mercury for a pointer motion of about 320° of arc is given the tests described for the gage calibrated in altitude. No test results are available on the pressure-indicating instrument. On the basis of the results on altitude-reading gages reasonable tolerances are as follows: Scale error, 0.25 inch of mercury; average change in reading due to temperature, 0.5 inch of mercury; change in reading at 30 inches of mercury due to temperature 0.2 inch of mercury; pointer oscillation under vibration, 0.2 inch of mercury; change in reading due to vibration 0.15 inch of mercury; and position error 0.1 inch of mercury.

BUREAU OF STANDARDS,
WASHINGTON, D.C., May 31, 1933.

REFERENCES

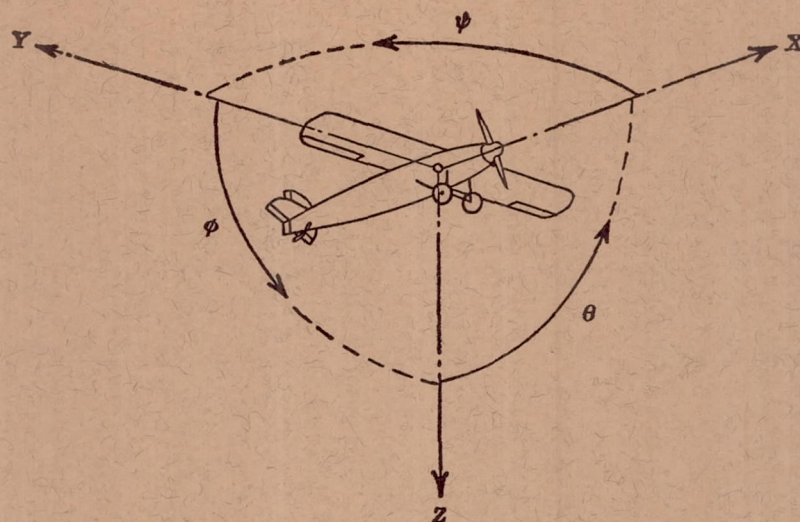
GENERAL

1. Campbell, Albert: On Test-Room Methods of Alternate Current Measurements. *Journ. Institution Elect. Eng.*, v. 30, p. 889, 1901.
2. Brooks, H. B.: The Accuracy of Commercial Electrical Instruments. *Journ. Amer. Inst. Elect. Eng.*, v. 39, p. 117, 1920.
3. Mendenhall, C. E.: Aeronautic Instruments. *Journ. Franklin Institute*, v. 191, p. 57, 1921.
4. Griffiths, E. A.: Engineering Instruments and Meters. D. Van Nostrand Co., 1921.
5. Bureau of Standards: Power Plant Instruments. N.A.C.A. Technical Report No. 129, 1921.
6. Keinath, G.: Die Technik der elektrischen Messgeräte. R. Oldenbourg, 1922.
7. Bennewitz, Kurt: Flugzeuginstrumente. R. C. Schmidt & Co., Berlin, 1922.
8. Drysdale, C. V., and Jolley, A. C.: Electrical Measuring Instruments. Ernest Benn, Ltd., 1924.
9. Diehl, W. S.: Standard Atmosphere Tables and Data. N.A.C.A. Technical Report No. 218, 1925.
10. Kinnard, I. F., and Faus, H. T.: Temperature Errors in Induction Watt-Hour Meters. *Jour. Amer. Inst. Elect. Eng.*, v. 44, p. 241, 1925.
11. Eaton, H. N., and others: Aircraft Instruments. Ronald Press, 1926.
12. Brombacher, W. G.: Recent Development in Aircraft Instruments, *Trans. A.S.M.E. Aero. Eng.*, v. 51, p. 119, 1929.
13. Air Corps: Aircraft Instruments. Pamphlet No. 1170-50, 1929.
14. Brombacher, W. G., and Melton, E. R.: Temperature Coefficient of the Modulus of Rigidity of Aircraft Instrument Diaphragm and Spring Materials. N.A.C.A. Technical Report No. 358, 1930.
15. Henrickson, H. B.: Thermometric Lag of Aircraft Thermometers, Thermographs and Barographs. *Bureau of Standards Journal of Research*, v. 5, p. 695, 1930.
16. Subcommittee on Instruments: Present Status of Aircraft Instruments. N.A.C.A. Technical Report No. 371, 1930.
17. Stewart, C. J.: Aircraft Instruments. Chapman & Hall, Ltd., 1930.
18. General Electric Co.: New Aircraft Indicating Instruments. *Instruments*, v. 4, p. 129, 1931.
19. Zand, S. J.: A study of Airplane and Instrument Board Vibration. *S.A.E. Trans.*, v. 26, p. 513, 1931.
20. Beij, K. Hilding: Aircraft Speed Instruments. N.A.C.A. Technical Report No. 420, 1932.

TACHOMETERS

21. Boudon, Alfred: Les Tachymetres Electromagnetiques (Magnetic Tachometer) *La Revue Technique*, v. 18, p. 388, 1897.
22. Benischke, G.: Elektrische Geschwindigkeitsmessapparate. *Electrotechnische Zts.*, v. 24, p. 401, 1903.
23. Watch and Clock Escapements. The Keystone, 1904 (Organ of the Jewelry and Optical Trades) 19th and Brown Sts., Philadelphia, Pa.
24. Lux, F.: Frahms Geschwindigkeitsmesser. *Zt. des Vereines Deutschen Ingenieure*, v. 48 II, p. 1580, 1904.
25. The Tel Revolution Indicator for Aircraft. *Flight*, v. 4, p. 943, 1912.
26. Esterline Electric Speed Indicator (d.c. generator type). *Elect. Rev. and West. Eng.*, v. 66, p. 829, 1915.
27. Wilke, W.: Drehzahl- und Fahrt Fernzeiger für Flugzeuge und Luftschiffe. *Der Motorwagen*, v. 21, pp. 461 and 492, 1918.
28. Wilke, W.: Untersuchung über Fliehkraft Tachometer nach dem Drehpendel Prinzip. *Zt. des Vereines Deutschen Ingenieure*, v. 62, pp. 801-809, pp. 829-835, 1918.
29. Feely, F. J.: The Van Sicken Chronometric Tachometer. *Aviation*, v. 8, p. 138, 1919.
30. Bureau of Standards: Testing of Airplane Tachometers, Air Service Information Circular, v. 1, No. 61, 1920.
31. Hunt, F. L.: Recent Developments and Outstanding Problems. N.A.C.A. Technical Report No. 132, 1921.
32. Pritschow, K.: Gerät zur Beobachtung umlaufender Teile in Scheinbarer Ruhe. *Werkstattstechnik*, v. 19, p. 246, 1925.
33. Seguin, L. and A.: A New Stroboscopic Method of Great Intensity. *Comptes Rendus*, v. 181, p. 539, 1925.
34. Hunt, F. L.: New Types of Aircraft Instruments. *Jour. Opt. Soc. Am. and Rev. Sci. Inst.*, v. 12, p. 227, 1926.
35. Lenckh, H. E., and Vieweg, R.: Über Stroboskopische Beobachtungen. *Archiv f. Elektrotechnik*, v. 15, p. 509, 1926.
36. Huey, C.: Tachometers, Revolution Indicators, Speed Indicators, and Revolution Counters. Types and Principles of Operation. *Journ. Am. Soc. Naval Eng.*, v. 39, p. 30, 1927.
37. Engine Revolution Indicator and Recorder for Aeroplanes. (Hasler-Tel Recorder) *Engineering (London)*, v. 124, p. 168, 1927. *Aero Digest*, v. 12, p. 196, 1928.
38. A C Airplane Tachometer. *Aviation*, v. 25, p. 281, 1928.
39. Stocks, C. W.: Motor-Vehicle Performance: Indicating and Recording Devices. (Hasler-Tel Recorder) *S.A.E. Journ.*, v. 27, p. 534, 1930.

40. Standerwick, R. G.: A New Form of Stroboscope. *Gen. Elect. Review*, v. 33, p. 566, 1930.
 41. Jones, D. A.: The R.A.E. Automatic Observer Mark IA. *Brit. Aero. Res. Com. Reports and Memo. No. 1405*, 1931.
 42. Speed-Measuring Instrument (Ashdown rotopscope). *Electrical Review (London)*, v. 109, p. 708, 1931.
 43. Hoff, W.: Research Work of the D.V.L. *Jour. Roy. Aero. Soc.*, v. 35, p. 778, 1931.
 44. Bartlett, B. W.: The Rotating Sector Disc. *Rev. Sci. Inst.*, v. 2, p. 96, 1931.
 45. Electric Speedometer (Stewart-Warner) *Automotive Ind.*, v. 64, p. 557, 1931.
- POWER-PLANT INSTRUMENTS OTHER THAN TACHOMETERS**
46. Lord Rayleigh: On the Bending and Vibration of Thin Elastic Shells. No. 152, *Scientific Papers*, vol. III, p. 230, 1887-92.
 47. Mauerer, L.: Deformation gekrümmter elastischer Platten. *Archiv. d. Math. und Physik*, Leipzig (3), v. 6, p. 1 and 260, 1903.
 48. Lemkes, C. R. L.: Pressure Gauges, Their Construction and Use. *Mechanical World*, Nov. 23, 1894.
 49. Wagner, E.: Metall Manometer als Hochdruckpräzisionsmeter. *Ann. d. Physik* (4), v. 15, p. 906, 1904.
 50. Klein, G.: Untersuchung und Kritik von Hochdruckmessen. Dissertation, Königl. Tech. Hochschule, Berlin, Sept. 1908.
 51. Lorenz, H.: Theorie der Röhrenfederanometer. *V.D.I.*, v. 54, p. 1865, 1910.
 52. Sunatani, Chido. The Theory of a Bourdon Tube Pressure Gauge and an Improvement in its Mechanism. *Sendai Univ. (Japan) Technologic Reports*, v. 4, p. 69, 1924.
 53. Fluid Meters, Their Theory and Application. Report of the A.S.M.E. Special Research Committee on Fluid Meters, part 1, second edition, 1927.
 54. Engine Temperature Indicator for Aircraft. *Instruments*, v. 2, p. 476, 1929.
 55. Kerr, P. S.: Fuel Flowmeters Designed to Measure Mass Flow. *Brit. Aero. Res. Com. Reports and Memo.*, No. 1245, 1929.
 56. New Airplane Gasoline Gauge. *Instruments*, v. 2, p. 467, 1929.
 57. Measuring Unconsumed Gases in Exhaust. *Aviation*, v. 30, p. 57, 1931. Also, Brochure by Motometer Gauge & Equipment Corp.
 58. Susa, Chas.: Determining Range of Helical Bourdon Springs. *Instruments*, v. 5, p. 85, 1932.
 59. Rolnik, H. A.: Deflection of Bourdon Tubes. *Instruments*, v. 6, p. 52, 1933.



Positive directions of axes and angles (forces and moments) are shown by arrows

Axis			Moment about axis			Angle		Velocities	
Designation	Sym- bol	Force (parallel to axis) symbol	Designation	Sym- bol	Positive direction	Designa- tion	Sym- bol	Linear (compo- nent along axis)	Angular
Longitudinal-----	X	X	Rolling-----	L	Y→Z	Roll-----	φ	u	p
Lateral-----	Y	Y	Pitching-----	M	Z→X	Pitch-----	θ	v	q
Normal-----	Z	Z	Yawing-----	N	X→Y	Yaw-----	ψ	w	r

Absolute coefficients of moment

$$C_l = \frac{L}{qbS}$$

(rolling)

$$C_m = \frac{M}{qcS}$$

(pitching)

$$C_n = \frac{N}{qbS}$$

(yawing)

Angle of set of control surface (relative to neutral position), δ . (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D Diameter

p Geometric pitch

p/D Pitch ratio

V' Inflow velocity

V_s Slipstream velocity

T Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$

Q Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$

C_s Speed-power coefficient $= \sqrt[5]{\frac{\rho V_s^5}{P n^2}}$

η Efficiency

n Revolutions per second, rps

Φ Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg-m/s = 550 ft-lb/sec

1 metric horsepower = 0.9863 hp

1 mph = 0.4470 mps

1 mps = 2.2369 mph

1 lb = 0.4536 kg

1 kg = 2.2046 lb

1 mi = 1,609.35 m = 5,280 ft

1 m = 3.2808 ft

